



Enterprise System-of-Systems Model for Digital-Thread Enabled Acquisition

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Executive Summary

In June 2018, the Office of the Secretary of Defense for Systems Engineering (DASD/SE) released the Department of Defense (DoD) Digital Engineering Strategy, a comprehensive strategy for the transformation of DoD engineering methods, processes, and tools to the digital age. The strategy outlines five strategic goals for the transformation, targeted to “promote the use of digital representations of systems and components and the use of digital artifacts as a technical means of communication across a diverse set of stakeholders, address a range of disciplines involved in the acquisition and procurement of national defense systems, and encourage innovation in the way we build, test, field, and sustain our national defense systems and how we train and shape the workforce to use these practices.” [1] These goals center on the definition, development, and use of a program “authoritative source of truth” – a government/contractor shared set of digital data and models that move away from static and disconnected program artifacts toward a fully integrated digital information exchange in order to improve the accuracy and timeliness of program decisions across the system lifecycle.

This report presents the results of a research project that was conducted in parallel with and independent of the development of that strategy to understand how that strategy might evolve and change the way the DoD conducts acquisition of new systems and supports existing systems. A multi-disciplinary research team conducted a qualitative analysis of that transformation, using interviews of over 25 stakeholders currently involved in Digital Engineering (DE) initiatives across multiple DoD agencies, NASA, and the FFRDC/UARC community. These interviews were then used to develop conceptual models describing what that future DoD acquisition enterprise might look like, given success of DoD DE initiatives. These conceptual models were developed independently from the released strategy, but the interview process found strong alignment with the strategy across the stakeholder base, so the models in this report were organized to align with the five goals of the DE strategy.

The research was targeted specifically on the impact of DE transformation to the DoD acquisition enterprise – the government program offices, acquisition professionals, and contractor practices that develop, operate, support, and maintain defense systems. It provides the first holistic assessment of how that transformation might evolve, and what benefits can be expected from the change. The research was conducted around a set of “central questions of interest” provided in initial interviews with DASD/SE sponsors. These are:

1. How will DE help the acquisition enterprise respond to the realm of the possible with warfighter needs?
2. What are the opportunities that can be gained from deeper information in the authoritative source of truth?
3. How will DE make the acquisition process more efficient and reduce rework?
4. Can DE make it easier to ingest new processes and incorporate acquisition expertise into acquisition tools?
5. How do DE documented architecture principles add value to development and acquisition processes?
6. How will DE environments capture and maintain lessons learned within and across programs?
7. How can DE improve the performance of the acquisition workforce, at every skill level?

These questions address the perceived value of the DE transition to DoD acquisition. The research methods used in this project are designed to bring focus to the value of enterprise level transformation outcomes and what are the leading indicators of change that would reflect achievement of those outcomes. The methods center on three questions: what are the desired change outcomes, who will lead/oppose the change and how will they interact to affect it, and what are the enablers and barriers to the change process? A set of qualitative tools were used to assess these questions – tools adapted from a large base of research on enterprise and innovation-driven transformation processes.

The project produced five conceptual models reflecting the future DE-enabled acquisition enterprise, one for each of the goals in the DE Strategy. The systemigram conceptual modeling tool, which includes both a narrative of change and accompanying concept diagram, was used to capture the combined views of the interviewed

stakeholders. The five models are 1) the Authoritative Source of Truth, 2) Digital Engineering to inform enterprise and program decision making, 3) the Digital Engineering infrastructure, 4) technical innovations to improve engineering practice, and 5) changing workforce and culture. These models were reviewed in a workshop setting with the sponsor team and approved for publication is this report.

In addition, the project conducted a workshop focused on how innovation will drive the DE transformation. This was a brainstorming exercise that produced an additional set of narrative “anecdotes” used to inform the conceptual models. The results of this workshop are also documented as a standalone result.

The model results had immediate use in informing the sponsor of potential metrics reflecting the performance or DE change initiatives. The systemigram diagram naturally produces insight on change metrics, which are the outcome of the relationships modeled in the diagram. In addition, the diagrams are useful in agreement on a lexicon that describes the future system, identification of all involved stakeholder groups in the process and their individual value sets, and identification of key enablers and barriers to enterprise change. These results are documented in the report.

Taken as a whole, this process provided significant insight on three central themes: what is the Authoritative Source of Truth how will it be provided, governed and used; how will DE transform the work that defense acquisition program offices perform, and how should they prepare; and how should the DoD enact change to their workforce and culture to ensure a successful transformation? The report identifies a set of recommendations for future research that addresses each of these themes.

1 Introduction and Background

The Department of Defense is embarking on a set of initiatives to transform DoD acquisition processes and guidance for engineering and manufacturing development in a full digitally enabled environment. The DoD Digital Engineering Strategy released in June 2018 outlines five strategic goals that reflect policy and guidance, support for pilot programs, support for implementation plans, and tools/standards [1]. The strategic goals are to:

1. Formalize the development, integration, and use of models to inform enterprise and program decision making.
2. Provide an enduring, authoritative source of truth.
3. Incorporate technical innovation to improve the engineering practice.
4. Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders.
5. Transform the culture and workforce to adopt and support digital engineering across the lifecycle.

The SERC is supporting Digital Engineering (DE) efforts through research tasks such as Transforming Systems Engineering through Model Based Systems Engineering and the Engineered Resilient Systems program. These efforts are focused on assessment and development of collaborative digital engineering environments as an evolution in processes, methods, and tools. However, additional research is needed to characterize the related path for the DoD acquisition enterprises: Digital Thread Enabled Acquisition.

Previous research in the SERC defined a set of methods and processes to model transformative change in large scale enterprises—the enterprise systems of systems methodology. In this research task, this approach will be used to develop enterprise transformation model that can be used to provide insight into the value of different acquisition strategies and incentives. “Owning the technical baseline” means that “[DoD] program managers and personnel have sufficient technical knowledge of their engineering development programs to ensure program success by making informed, timely, and independent decisions to manage cost, schedule, and performance risk while ensuring disciplined program execution.” [2] Owning the technical baseline will allow DoD to respond more quickly and without disruption to changing mission needs and to opportunities for technical innovation. Central to this is the DE strategy to establish an enduring, authoritative source of truth.

This project was conducted to better understand how DE will support owning the technical baseline and how it will affect the corresponding acquisitions processes. The Digital Thread, Digital Twin, and Model-Based Systems Engineering (MBSE) are key enablers that will allow Program Managers (PMs) to reduce both technical and programmatic risk through better interface management, deeper collaboration, understanding the impact of design choices on cost and schedule, etc. It is expected that this impact could reach much further, not only changing the way information is shared in the acquisitions context but fundamentally changing the business eco-system: competition, risk attitudes, business models, etc.

The transformation from a primarily paper-based set of decision tools to a digital enterprise will likely make a number of current business processes obsolete, change current relationships between the defense acquisition community and the defense industry, adjust roles and associated jobs, and shift stakeholder perspectives on value in the enterprise. One should expect that the various policy makers, user communities, acquisition communities, and contractor communities will both embrace and oppose transformative changes in ways that maximize their individual values. How these complex interactions among stakeholders will affect the acquisitions eco-system is difficult to predict.

This research was conducted to evaluate the impacts of DE on current DoD acquisition enterprise processes. The following questions guided the research:

- What changes are likely to emerge from the transition to DE processes, methods, and tools?
- What are the enablers and barriers to such innovation in the DoD acquisition enterprise?
- What stakeholders will be affected and how will they likely embrace or oppose change?
- How might stakeholders be incentivized to embrace innovation and how will this be measured?
- What are the leading and long-term indicators of change?
- How might the value of such changes be predicted and measured?

Within this acquisitions enterprise, major areas of competing goals will include shared government and contractor access to the set of design data, scientific and technical analyses, decision trades, process and tool data, development approaches, and even engineering notes and discussions that form the project technical baseline. Shared goals will not be developed with mandates, but will be enabled through innovations in methods, processes and tools that create “win-win” strategies between stakeholders. Changes that focus on the enablers and barriers to effective innovation in these processes are needed, and these are the primary drivers of an enterprise view.

While MBSE is well-developed and broadly adopted in the defense industry and beyond, the full scope of a DE transition is still in the early stages of development and adoption. Besides the DoD efforts on digital engineering, several similar efforts are underway in industry: digital threads (Air Force), digital twins (by GE or Siemens), digital tapestry (Lockheed Martin), model-centric engineering (JPL/NASA), etc. Although digital or model-based approaches towards systems engineering and acquisitions are clearly the path to the future, there are still significant hurdles to overcome. In addition, most of the advances so far have focused on better support for traditional SE methods in a traditional acquisitions context. In this research task, the aim was to lay the foundation for a digital thread enabled acquisitions ecosystem in which the processes (and potentially even organizational structures) are updated to best take advantage of the new digital engineering capabilities. The questions of how the acquisitions ecosystem will be affected by digital engineering and how best to facilitate the corresponding transformation are the focus of this report.

In particular DE will integrate systems engineering, product design, development processes, program management, and related documentation—providing much greater access to and insight into the program technical baseline. How the government and industry participate together in the process, and share appropriate baseline data, is an area that will create both significant value and risk. Identifying the components of the process and baseline that create shared value is critical, and enabling innovations that enable trusted collaboration will build a pathway for success. An enterprise model is needed that identifies appropriate integration of the people, resources, processes, institutional outcomes, and policy changes that in the long-term will transform the acquisition enterprise. This research task has been the first step toward developing that model.

The task used a qualitative research method based on structured interviews to derive a holistic model of the defense acquisition enterprise transition to DE. The generated interview data was encoded and diagrammed in a conceptual model using the systemigram formalism [3]. The conceptual model was generated via a series of narratives generated in the interview process, and refined in design workshops with key stakeholders in the enterprise. This method follows a formal process for documenting enterprise transformation as a multi-level model previously developed and demonstrated in SERC Enterprise Systems-of-Systems (ESoS) research [4] [5].

An interview protocol was developed to encourage a diverse set of DE stakeholders to speak openly about the process of DE enterprise change. The project interviewed over 25 stakeholders across 15 project visits, and the resulting interview responses were used to create a consolidated narrative describing the transition process. The anecdotes provided by these stakeholders were then diagrammed using the systemigram process that creates a

combined narrative and diagram of key aspects of the “story.” In the interview process, the research team found strong consistency between the interview narratives and the DoD DE Strategy, even though that document was published at the end of the process. Based on consistency of these views, the systemigrams were organized into 5 narrative/diagram sets – one for each goal in the DE Strategy document. The systemigrams were reviewed in a workshop with the DE Strategy authors and updated from that workshop to form the basis of this report. Section 2 of the report describes the methodology used, and Section 3 provides the systemigrams.

Because an enterprise transformation is an innovation process that unfolds over time and with many incremental advances, and additional workshop was conducted with the sponsor team to help understand the associated innovation landscape that will drive the DE transformation. The workshop used the “Three Horizons” facilitation tool to map that innovation landscape [6]. These results are presented in Section 4.

The process of developing the conceptual models of transformation leads to a set of initial artifacts that can be used to computationally model the transformation process. These are identification of key stakeholder groups and their values, identification of potential metrics that would reflect the process of transformative change, and identification of enablers and barriers to change that must be incentivized or overcome to succeed. These are discussed in Section 5. In addition, the systemigrams provide an initial broad lexicon that can aid in agreement on key terminology and model ontology for future use. Section 5 includes an initial presentation on this topic.

This report documents the initial stage of an enterprise transition model – the conceptual definition. Section 6 provides a discussion of next steps and future research that would be needed to build a set of computational models of enterprise change.

2 Methodology

This section discusses the research methodologies used in the research task reported here.

2.1 METHODOLOGY BACKGROUND

This task employed a research methodology informed by communities of practice in enterprise transformation, system-of-systems, innovation systems, and social innovation fields. The primary resources for the modeling process documented herein derive from previous SERC research on Multi-Level Socio-Technical Modeling and Enterprise Systems Analysis [4] [5]. The SERC Enterprise Systems Analysis line of research is to develop and evaluate a methodology for modeling and analyzing enterprise systems. This work defines an enterprise system as a set of interacting organizations that serve a purpose yet have no locus of control (the DoD acquisition enterprise meets its goal).

The qualitative facilitation methods used were further developed in the Assessing Innovation Impact Potential Toolset developed by the Global Knowledge Initiative and Georgia Tech Research Institute under sponsorship of the Rockefeller Foundation [6]. These methods were developed as a forward-looking process to provide decision makers with greater insight and confidence into the process of assessing the potential of innovation to impact a problem or change strategy. The result was a customizable toolset to assess the future impact that innovation can deliver in a system to tackle particularly complex problems.

Both of these toolsets are targeted at holistic analysis and understanding of large complex sociotechnical systems of systems. Understanding and classifying the social and technical aspects forms the starting point for analyses of SoS behavior in sociotechnical enterprises. The analysis supports a human-centered or participatory approach to understanding and designing SoS change. Sociotechnical SoS demonstrate several consistent patterns that are relevant to human enterprises which have been studied by a number of authors. Table 1 lists these characteristics:

Table 1. Architectural patterns of sociotechnical SoS

Autonomy or multi-agent interaction	Individual agents in the system operate autonomously, adapt, and learn as they interact over time
Heterarchy	Aspects of sociotechnical systems are heterarchical in nature and lack the hierarchical control mechanisms inherent to systems engineering. Agent behaviors result in self-organization, and behaviors emerge from agents, not from design
Multi-scale or multi-layer hierarchy formation	Sociotechnical systems tend to self-organize at lower layers and then create hierarchies as they grow in size, usually driven by series of events. The behaviors that develop at higher layers do not necessarily reflect the behaviors of individual agents or groups
Emergence	Behaviors and properties emerge from interactions that are representative of the whole of a system, and not present in any of the constituent agents or parts
Evolutionary development	Goals and objectives, as well as structure and functionality, are in constant change as entities are added, modified, and removed. However, the evolution of the whole happens slowly in comparison to individual agents or components [7]
Command and control	Sociotechnical systems have no single mechanisms of control. Behaviors arise from leadership and incentives instead of authority and control. The architect must design interventions that influence change in the systems
Connectivity	Evolution in the systems is driven by connectivity, communication (information flow), and collaboration both within and outside of the systems
Complexity	The systems are sufficiently large in terms of number of physical connections and information-driven interactions that they cannot be fully analyzed by conventional (i.e. mathematical) descriptions of system behavior [8]

The research followed a defined process to accelerate stakeholder learning in the domain of a complex sociotechnical SoS architecture that highlights the eight characteristics listed in table 1, and causes the SoS architect to directly experience them in both participatory sessions with stakeholders and in study settings. These are captured in an analysis of the SoS which includes six processes, as listed in Table 2. This is a structured process that walks the participants through selected stakeholder perspectives, helping to define the SoS, building representative abstractions at different layers of the SoS, agreeing on outcomes, understanding flows, and finally designing alternative implementations of the SoS.

Table 2. Architectural analysis of a sociotechnical SoS

SoS Perspectives	The tension between perceptions and facts often form the best starting place to understand the behaviors in a sociotechnical system. Understanding perspectives is a stakeholder research process best informed by talking to stakeholders but that also can be created with selected readings that highlight emergence.
SoS Definition	A systems thinking oriented process where the researchers have to identify context (or boundaries of analysis), appropriate levels of analysis, and enablers or barriers that might exist in the context of interest.
Multi-layer Abstraction	Identification of all of the actors at each societal layer and “what they bring with them” - what abstractions would represent primary performance measures of the current SoS and the desired evolution.
SoS Outcomes	Modeling all dimensions of the SoS considering system outputs, outcomes (or goals), and the interactions that cause them.
SoS Communication	Identification of information flows that are relevant to decision making in the sociotechnical system. This should include transparency (availability to all parts of the system), timeliness (to make decisions), accuracy, and trust
SoS Implementation	Sociotechnical systems have no single mechanisms of control. Behaviors arise from leadership and incentives instead of authority and control. The architect must design interventions that influence change in the SoS

Well-structured narratives in the system architecting process are critical to the understanding of emergence [9], which is core to the Enterprise SoS evaluation. Purposeful development of such narratives provide the architectural context needed to engage the stakeholders in a discussion of the SoS characteristics. The narrative serves as a mental expression of different events, phenomena, or observations as episodes that have meaning in the mental domain of the stakeholders [10]. Thus, the process of determining Enterprise SoS perspectives begins with a narrative. This process is at the center of the research documented in this report and the tools used provide an example of the insight that can be gained by analyzing a complex enterprise like the DoD acquisition enterprise in this way.

David Snowden, in his research on narrative knowing in complex enterprises, discusses the use of narrative fragments or “anecdotes,” in contrast with full stories, as enabling the researcher to create a blend of stakeholder anecdotes with their understanding of the situation to create a contextually meaningful course of action or strategy [11]. The anecdotes that people relate to the larger story, when queried, become like components of the system in a human centered design process, allowing relevant explanatory models to be built that conceptualize the whole of the system. To explain potential emergence in an Enterprise SoS, the research team collects anecdotes that discuss the present enterprise and possible emergent changes in the future, which are collected with interviews or other facilitation tools. These are collected into a formal framework for modeling the enterprise discussed in the next section.

2.2 ENTERPRISE SoS ANALYSIS METHOD

The core of the enterprise SoS analysis process is a 10-step data collection and characterization methodology for modeling complex systems [4] [5]. Shown in table III, The initial steps are intended to carry background research into an expert forum where the critical aspects of the research are evaluated via interviews or in a workshop setting.

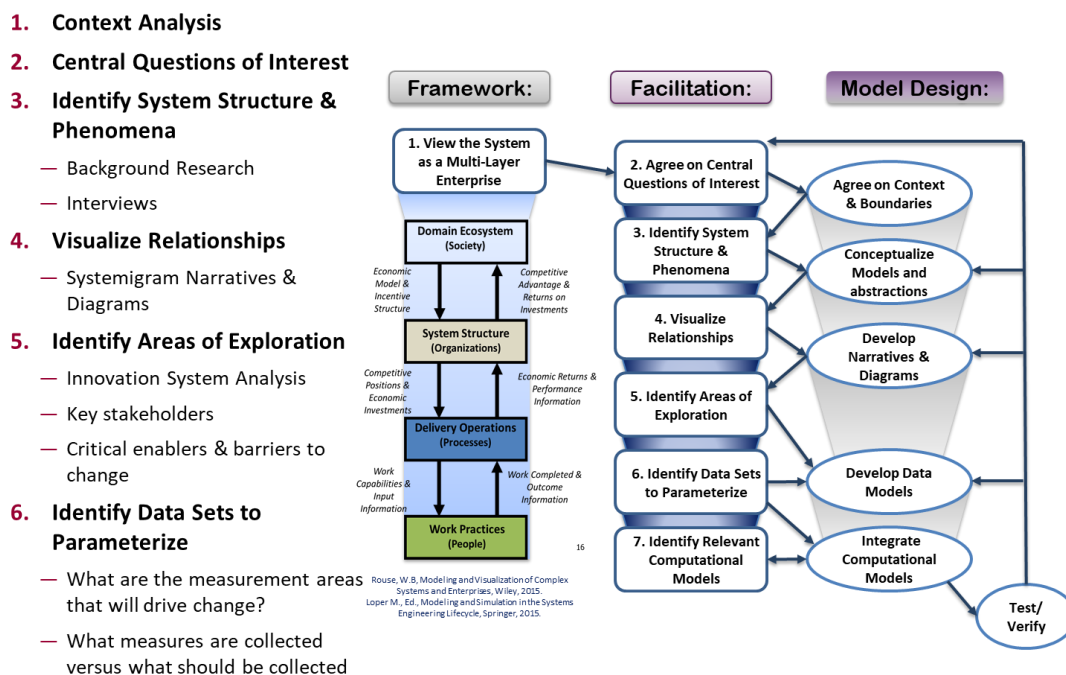
Table 3. 10-step enterprise analysis process.

Step 1	Decide On the Central Questions of Interest
Step 2	Define Key Phenomena Underlying These Questions
Step 3	Develop One or More Visualizations of Relationships among Phenomena
Step 4	Determine Key Tradeoffs That Appear to Warrant Deeper Exploration
Step 5	Identify Alternative Representations of These Phenomena
Step 6	Assess the Ability to Connect Alternative Representations
Step 7	Determine a Consistent Set of Assumptions
Step 8	Identify Data Sets to Support Parameterization
Step 9	Program and Verify Computational Instantiations
Step 10	Validate Model Predictions, at Least against Baseline Data

The purpose of this effort is not to arrive at a set of answers, but to arrive at an understanding of how the enterprise is organized and might change in response to emerging systemic changes.

The comments and information gathered from stakeholder narratives are fed into the first steps of the 10-step methodology to lay the foundation for the study and modeling efforts. All steps will not be completed for this effort as the project will not be creating a computational model, however all steps are included in Table 3.

Figure 1 provides a graphical depiction of this process as tailored for this project. Figure 2 describes the primary analysis tools. The analysis starts with an organizational framework that represents a complex enterprise as a multi-layer enterprise architecture. The process uses a brainstorming tool called a context analysis matrix to aid in understanding of the enterprise at multiple layers and identifying primary abstractions for a model at each layer. The context analysis tool is discussed in Appendix A.

**Figure 1. Full Enterprise Analysis Process and Process Steps.**

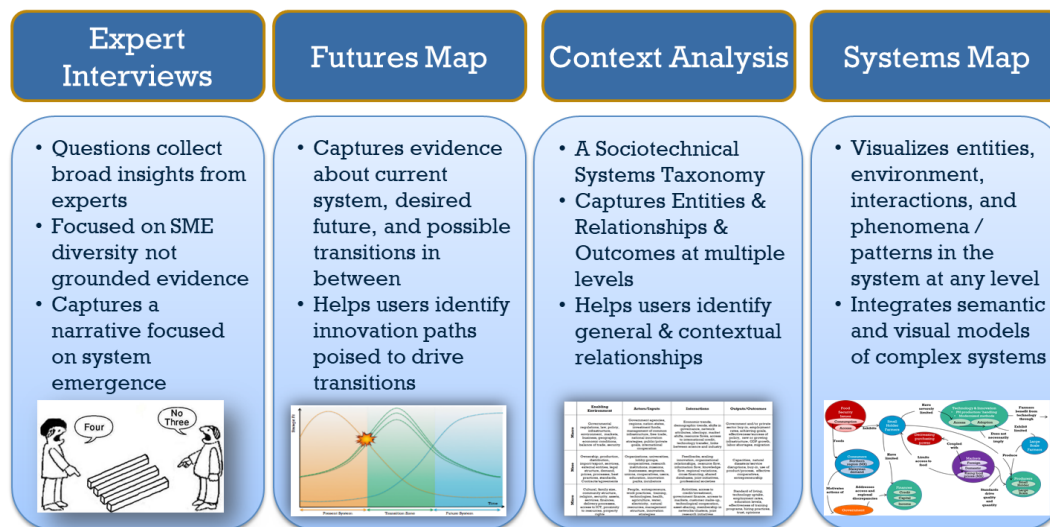


Figure 2. Primary facilitation tools

From that artifact, a discussion with the primary sponsor of the project produces a set of “central questions of interest.” These are the questions the resulting model should answer. This step serves to set boundaries for the model to a context and strategy focus where specific outcomes can be identified. From here the process attempts to map the enterprise using a series of stakeholder interviews, expert workshops, and background research.

The project used a unique interview protocol developed from theory of innovation driven transformation to elicit narratives from key stakeholders who are familiar with DE initiatives in the U.S. government. The interview protocol is structured around discussions of possible emergent futures. It is a purely qualitative in nature, and is designed to collect a breadth of perspectives from as diverse a stakeholder set as possible. The interview protocol is provided and discussed further in Appendix B.

In addition to the interview process, a futures map is used to focus on the innovation pathways that will enable the enterprise transformation. The futures map is created in a facilitated workshop setting using the Three Horizons tool for transformative innovation [12]. This method is discussed further in Appendix C.

Once the data collection is complete, an enterprise system map is created from the various perspectives and anecdotes collected in the interviews, context analysis, futures map, and additional desk research. The system maps are developed using the narratives collected and a systemigram diagram. The interview narratives from the core of the systemigram process. In this project, over 70 pages of collected interview transcripts were consolidated into a single 11-page enterprise narrative organized thematically. This narrative development process is the first part of “art” of the methodology, best performed by researchers experienced in the process.

Once the completed consolidated narrative is finished, the research team gathers to create the systemigrams. While the systemigram narrative and diagrams naturally span multiple layers of the multi-layer enterprise model, it is important to focus at least one systemigram on each of the four layers of the enterprise in order to gain a complete insight into the enterprise change. Systemigram diagrams are created by literally mapping text phrases in the consolidated narrative into the diagram in a noun-verb-noun phrase format. The diagrams are constructed using the systemigram formalism discussed further in Appendix D, focusing on extracting the appropriate components of the larger narrative in relation to the systemigram “story” and building a diagram that can be used to engage a stakeholder discussion of the story. Initial validation of the systemigrams is then completed in a workshop facilitation with key stakeholders that discusses and updates the “story” in the diagrams. The systemigrams form the central conceptual modeling artifacts of the research for further use. However, they do represent the exact words of the stakeholders in the interview process and modeling success is dependent on effective elicitation of stakeholder perspectives.

At this point the systemigram diagrams and other artifacts can be used to begin structuring more formal models. The end goal is to provide a set of conceptual modeling artifacts that inform computation models of enterprise organizational change strategies. These are left to later research in future project phases.

An immediate outcome of the process is the generation of a lexicon or terminology for the system. This is a natural outcome of the narrative process, as the narrative consolidations will integrate multiple stakeholder descriptive terms around model components. It is recommended that terminology is agreed upon by the stakeholder community before computational models are constructed. Section 5.1 reports on an initial Lexicon developed from the model focused on information exchange.

The systemigram diagrams are then used, by studying the relationships in the diagrams, to identify a set of metrics that will serve as leading and long-term indicators of enterprise change. This is associated with Steps 5 and 6 of the Enterprise Analysis process of Figure 1. These measures serve as the primary input and output measures of a computational model set. An initial list of metrics is provided in Section 5.2, but these have not been through stakeholder review and will be further refined in follow-on research.

The other immediate process is to use the diagrams to conduct an innovation system analysis. This consists of two structured reviews: identification of key change actors in the system (stakeholders for and against) and their primary values or stakes in the outcomes, and identification of key enablers and barriers to change. These will be discussed in sections 5.3 and 5.4, respectively.

2.3 INSTITUTIONAL REVIEW BOARDS

All stakeholder interview questions and the process were approved independently by Institutional Review Boards (IRBs) at Georgia Institute of Technology at University of Alabama-Huntsville, the primary institutional performers on the project in the interview phases. In addition, both IRB processes were reviewed and approved by the government sponsor IRB. The interviews were completely voluntary, and all collected interview data was anonymized to protect the identity of the contributors. No compensation was provided to any interviewee.

The following procedures were followed to keep personal information confidential in this study: The data collected about participants is kept private to the extent allowed by law. To protect privacy, interviewee records are kept under a code number rather than by name. All records are kept in locked files and only study staff are allowed to look at them. The interviewee name and any other information that might point to them does not appear in the published results of this research. Now that the study is complete, all records identifying the interviewees are being disposed of and deleted from all digital files. Participant privacy will be protected to the extent allowed by law. To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology or University of Alabama-Huntsville IRBs may review study records.

3 Context Analysis, Interview Narratives, and Systemigram Models

This section provides the consolidated narrative and diagram for each of the five DE strategy initiatives. The process starts with the context analysis tool, which is a way to organize information reflecting what are the desired change outcomes, who will lead/oppose the change and how will they interact to affect it, and what are the enablers and barriers to the change process. This set of information drives the development of the systemigrams. After the context analysis results, a short discussion of how to read a systemigram is introduced first, followed by each of the five systemigrams:

- 1) The Authoritative Source of Truth
- 2) Inform Enterprise and Program Decision Making
- 3) Digital Engineering Infrastructure
- 4) Technical Innovations to Improve Engineering Practice
- 5) Changing Workforce and Culture

3.1 CONTEXT ANALYSIS TOOL

The context analysis tool is used to organize essential information reflecting desired change outputs/outcomes, actors and institutions who will lead/oppose the change, activities they perform and how will they interact to affect change, and what are the enablers and barriers to the change process. These are each organized into the four layers that reflect typical enterprise architectures: people/work activities, processes, institutions, and domain or ecosystem. The context analysis was matured in several stages:

- 1) An initial matrix was developed by the project team using background research on DE initiatives.
- 2) A brainstorming workshop was facilitated with the sponsor team to fill out the details based on their knowledge and information.
- 3) The resulting matrix was reviewed with the project ultimate sponsor (DASD/SE level) in order to capture a definitive project set of “central questions of interest” and their related information. This is necessary to scope and bound the research.
- 4) A final version was developed based on an internal team workshop to organize the systemigram, the matrix was reorganized and updated to focus on the five DE strategy outcomes.

Table 4 reflects the complete research team/sponsor team context analysis matrix at the completion of stage 3. Table 5 reflects the final context analysis matrix used to organize the systemigrams in stage 4. The final version pulled in the primary goals and sub-goals of the DoD DE strategy document as the organizing outcomes/outputs. In the matrix the numbering in the outcomes/outputs column reflects the numerical organization of goals and sub-goals documented in the DoD DE Strategy.

Table 4. Initial Context Analysis

	Enabling Environment	Key Actors & Resources	Interactions/Activities	Outcomes/Outputs
Domain	<ul style="list-style-type: none"> Operational Context & history Aging Workforce WSARA, DAA Standards FARS 	<ul style="list-style-type: none"> Public opinion Global Innovation Congress Model-based acquisition community 	<ul style="list-style-type: none"> Political Climate Budget/ investments Evolved policy, guidance, specifications, and standards Curate models across domains, fidelity, phases and the lifecycle 	<ul style="list-style-type: none"> Goal 1: Formalize the development, integration and use of models to inform enterprise and program decision making Oversight Increased preparedness Consolidating & standardizing operations Map latest needs with realm of the possible
Institutions	<ul style="list-style-type: none"> Threats National & global supply chain Not agile Develop, mature, and use IT infrastructures Define and govern authoritative source of truth Value added to the organization 	<ul style="list-style-type: none"> DCMA DCAA (auditing) Defense contractors FFRDC's and UARC's DoD Acquisition DoD Program Offices Sustainment programs NASA INCOSE and other professional organizations MBSE processes Army, Air Force, Navy, Marine Corps, and Coast Guard 	<ul style="list-style-type: none"> Adherence to FAR Win funding Return on investment Compliant proposals Digital Thread/Twin Analysis of cost, schedule, performance, risk - exploration Program decisions Framing assumptions Sharing best practices Use authoritative source of truth across the lifecycle Common operating environment 	<ul style="list-style-type: none"> Goal 2: Provide an enduring authoritative source of truth Goal 4: Establish a supporting infrastructure and environment to perform activities, collaborate, and communicate across stakeholders Greater flexibility/ adaptability in design Confidence in performance as expected Improve enterprise decision making (better substantiation) Program performance Knowledge capture Responsive with quality Reduced stovepipes
Processes	<ul style="list-style-type: none"> DoDI 5000.02 Defense Acq Guidebook Lifecycle development Taxonomies, ontologies Existing contractual practices and tech data management DOD CPMS: Civilian Strategic Human Capital Planning Connect micro to macro 	<ul style="list-style-type: none"> Tailoring instructions Standards, DAGs Hardware & software tools DE methods Models and data sources Always working off the latest source of information 	<ul style="list-style-type: none"> NDAA Process as the outcome Program reviews, communications Trust & data managing Secure & Protect IP Modeling & Simulation Control of models & data Data collection & mgmt. Requirements Knowledge mgmt. Inform program & decision making 	<ul style="list-style-type: none"> Goal 3: Incorporate technical innovations to improve the engineering practice Increased efficiency in acquisition practice Increased efficiency in engineering practice Lower cost/faster schedule – reduce rework Transparency Enhanced Communication Disruption/continuity More Entrepreneurship & Innovation in W.S. Tech validation & rationale Environments that reflect lessons learned Easier to ingest new processes Virtual collaboration
People	<ul style="list-style-type: none"> Education & training Experience Comfort with technology Usability of DE methods & tools Organizational and cultural resistance Management support/advocacy Common operating environment Professional development 	<ul style="list-style-type: none"> Program managers Warfighters End users Modelers Systems Engineers Design Engineers New technology Leadership & expectations Older vs younger workforce Human Capital Management A-Teams & B/C-Teams 	<ul style="list-style-type: none"> Accurate Technical information Communication of expectations Managing \$\$ Communicate the DE transformation vision & strategy Establish accountability Build coalitions Rigorously use models Quantitative vs qualitative results Vertical vs Horizontal work structure 	<ul style="list-style-type: none"> Goal 5: Transform Culture and Workforce Integration & use of models Informed decision making Greater insight, more rational decisions Advancement of the DE knowledge base Skewed results Overreliance on quantitative data Greater flexibility/adaptability in design Automate workflow processes (as applicable) Changing workforce demographics Expertise incorporated into the tools Deeper information available to decision makers

Table 5. Final Context Analysis

	Enabling Environment	Key Actors & Resources	Interactions/Activities	Outcomes/Outputs
Domain	<ul style="list-style-type: none"> Operational Context – increasing complexity DoD DE Strategy Aging workforce Emerging standards 	<ul style="list-style-type: none"> Manufacturing 4.0 drivers Global innovation in DE Congress Model-based acquisition communities 	<ul style="list-style-type: none"> Political Climate Budget/investments Evolved policy, guidance, specifications, and standards Curate models across domains, fidelity, phases and the lifecycle 	<ul style="list-style-type: none"> Goal 1: Formalize the development, integration and use of models to inform enterprise and program decision making 5.1: Improve the DE knowledge base Map the realm of the possible with warfighter needs
Institutions	<ul style="list-style-type: none"> Threats National & global supply chain Not agile Develop, mature, and use IT infrastructures Define and govern authoritative source of truth Value added to the organization 	<ul style="list-style-type: none"> DASD/SE Service level Program Offices & Program Executives DCMA DCAA (auditing) Defense contractors FFRDC's and UARC's DoD Sustainment centers NASA INCOSE and other professional organizations Tool vendors Cloud providers JCIDS Joint Staff/ Operational planners 	<ul style="list-style-type: none"> Adherence to FAR Win/maintain funding Return on investment Better Compliant proposals Analysis of cost, schedule, performance, risk - exploration Sharing best practices Use AST across the lifecycle Digital program documents Enterprise owns the ontology and data layer for analytical approaches Libraries of reusable models Pay once for data, reuse everywhere 	<ul style="list-style-type: none"> 1.1: Formalize the planning for models to support engineering activities and decision making across the lifecycle 1.2: Formally develop, integrate, and curate models Goal 2: Provide an enduring authoritative source of truth (AST) 2.1: Define the AST 3.1: Establish an end-to-end DE enterprise Goal 4: Establish a supporting infrastructure and environment 4.1: Develop, mature, and use DE IT infrastructures 5.2: Lead & support DE transformation 5.3 Build and prepare the workforce
Processes	<ul style="list-style-type: none"> DoDI 5000.02 Defense Acq Guidebook Lifecycle development Lexicon, taxonomies, ontologies Existing contractual practices and tech data management DOD CPMS: Civilian Strategic Human Capital Planning Library-esque license usage Paperless system and technical information 	<ul style="list-style-type: none"> Process developers: Tailoring instructions Communities: Standards, guides Hardware & software tools Central data storage and portal DE methods & tools DE initiatives/pathfinders Model providers and data sources Communicators/matchmakers Tech data procurement Training programs Model governance/version control mgmt. Better informed Decision makers 	<ul style="list-style-type: none"> Program reviews, communications Secure & Protect IP Metrics Qty of test data on models is sufficient to enable trust Knowledge capture & transfer Digital twin that injects data back into the models System data accessible from a single portal Eliminate human process of finding and using data Everything needed is on desktop, what's been done before is there to reuse Product and manufacturing information match physical systems 	<ul style="list-style-type: none"> Goal 3: Incorporate technical innovations to improve the engineering practice 3.2: Use technological innovations to improve the DE practice 2.2: Govern the AST 2.3: Use the AST 4.2: Develop, mature, and use DE methodologies 4.3: Secure IT infrastructure and protect IP opportunities that can be gained from deeper information in the AST make the process more efficient and reduce rework capture and maintain lessons learned
People	<ul style="list-style-type: none"> Education & training Experience Comfort with technology Usability of DE methods & tools Organizational and cultural resistance Management support/advocacy Common operating environment Professional development Learning systems that adapt to individual abilities 	<ul style="list-style-type: none"> Program managers Warfighters End users Modelers Systems Engineers Design Engineers New technologies Leadership & messaging Older vs younger workforce Human capital - skills A-Teams & B/C-Teams - performance 	<ul style="list-style-type: none"> Enhance collaboration Accurate Technical information Communication of expectations Community of Interest/Practice Vertical vs Horizontal work structure Establish accountability Rigorously use models Quantitative/qualitative results Risk informed analysis Humans can focus on creative work and machines can take care of mundane tasks Understand incremental value of all trades, done dynamically 	<ul style="list-style-type: none"> Goal 5: Transform Culture and Workforce 1.3: Use models to support engineering activities and decision making easier to ingest new processes and incorporate acquisition expertise into the tools make the B-team and C-team players perform more at the A-Team level

The context analysis serves as a basis for the project team to collect information and determine the primary abstractions that exist at each level of the enterprise. In the modeling context, it is important to understand how different abstractions relate to each other and aggregate to the next level. This helps overcome the assumptions that are made about lower level performance measures and activities. Because one layer can effectively only enable or inhibit another, it also helps to identify primary enablers and barriers of change.

The research team, as they become immersed in these anecdotes and develop domain knowledge, becomes better prepared to interpret the interview data and to develop the systemigrams.

3.2 HOW TO READ A SYSTEMIGRAM

When a problem or issue is sufficiently complex or unstructured there is a period of information collection that is a first step to defining potential engineered solutions. A set of heuristics guides that collection. The results of that collection may be unstructured itself but basic tools like mind maps can be immediately used to start structuring the space. This process builds a “model framework” for the system. The model framework is a conceptual view of the system model that captures key characteristics like boundaries, organizations, stakeholders, policies, information flows, etc. It is in effect capturing the architecture of the system with respect to the problems or issues at hand.

Checkland’s Soft Systems Methodology recommends that we express problems, issues, or opportunities in the situation system where they are encountered before proceeding to a conceptual modeling phase. At this point verbal narratives or picture diagrams are most effective at expressing the situational aspects. This narrative describes a problem, but to introduce solutions to the problem you need to understand the variables that form the root cause of the situation. At this point more formal modeling becomes useful. However, it is difficult to communicate the dynamics of the system with a computational model. An interim step that provides a visual model of the system and the context of the issue at hand is needed. Checkland introduces the concept of rich pictures here.

Blair, Boardman, and Sauser developed a formal visualization approach call the “Systemigram” that captures the conceptual model in a systems context and provides a good way to transition between narrative and computational modeling [3]. The systemigram combines a narrative discussion of the system and transformation strategy with a 1-page diagram that models the narrative as a set of nodes and links. When used properly the systemigram provides the architecture of the system that can be used to guide creation or use of more computational models. It is developed from the narrative text, which may be a compelling descriptive view of the system and its dynamics, or a strategic text written to analyze the behaviors of the system and directly produce the diagram. A formal use of the systemigram tool is guided by the following basic rules:

1. The diagram fits on a single page.
2. There is a beginning and an end; the main flow of the story is upper left to lower right.
3. Entities are nodes, links, inputs, and outputs. Nodes are key concepts, phrases, or nouns representing entities or conditions.
4. Links represent relationships and flow between nodes; they include verb phrases identifying transformation, belonging, and being. Links should not cross each other.
5. Nodes may contain other nodes identifying other diagrams or groups. This supports understanding of multi-layer abstractions and aggregation points.
6. The layout of the diagram should be arranged to bring attention to the different levels of perspective it the system. Think “why,” “what,” and “how.”
7. Color is used to highlight particular concepts and transformations. In the diagrams to follow the colors are used to represent the four different enterprise layers.

3.3 SYSTEMIGRAM 1: THE AUTHORITATIVE SOURCE OF TRUTH

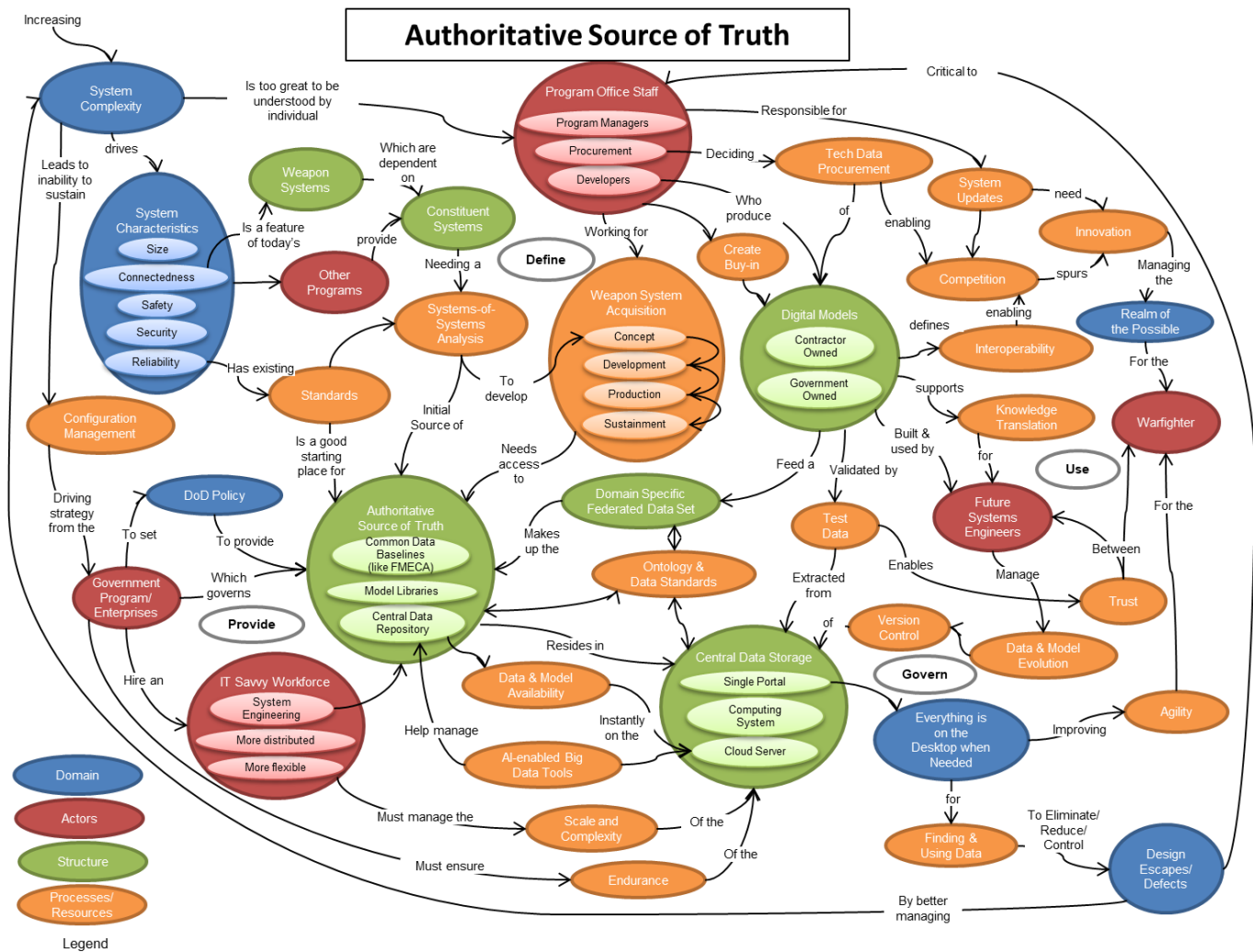


Figure 3. Systemigram 1: The Authoritative Source of Truth.

Questions linger over what is considered to be the Authoritative Source of Truth (AST) and why the government should pursue DE and the AST. As to why, increasing system complexity is driving today's system characteristics like size, connectedness, safety, security, and reliability. Today, a major acquisition development program is dependent on other programs and systems, and these characteristics have become dominant features in weapon systems. New weapon systems are dependent on multiple constituent systems, and effective documentation of architecture and robust system of systems analysis has become a necessary step in the development of new system concepts. Management of complexity across the conceptual, development, production, and sustainment must have access to a large set of historical and current operations data. As to what, this is the authoritative source of truth - the central data repository for all program information. The system of systems analysis, completed in the concept phase of a new system, provides the initial source of truth data. However, this is a significant change in the way systems are developed today. It will be a learning process to evolve exactly what the AST contains. Reliability related design, test, and performance data is a good place to start because there are existing data standards in this community to build from. Common data baselines like Failure Modes, Effects, and Criticality Analysis (FMECA) are created in the community today. As model based systems engineering becomes more prevalent, the AST will become the central repository for all program data and various model libraries, and additional standards like FMECA will be created to organize and aggregate the data across the program lifecycle.

With increasing complexity, the systems engineering community is in general agreement that they can no longer effectively sustain configuration management in SoS. Following other industries like logistics and finance, there is need for data-driven configuration management strategies. This is pushing government and program office enterprises to set DoD policy for DE transformation and a move from paper program baselines to the data-driven AST. Government program offices will most likely govern the AST for a program, but it will consist of a number of domain specific federated data sets that come from various government entities and contractors.

In addition, the community has come to understand that the level of system complexity today is too great for any individual program office staff to maintain wide enough system knowledge to effectively make decisions related to program management, procurement, and development of these systems. Program offices must produce the digital models and data or obtain these from contractors. Government engineering teams will produce digital models that will be exchanged with contractors, who in turn will exchange their models with the government sponsors. This should gradually replace paper specifications and architecture frameworks to feed the domain specific federated data sets. Procurement staff in the program offices will work with engineering to make decisions on tech data procurement early in the development programs. Leadership in program offices must create buy-in between government and contractors for the shift to digital models and away from paper.

The AST will reside in a central data storage repository, most likely a cloud server. In order to achieve this cloud model, a significant effort in ontology development and data standards is needed. The AST will be data and models that are instantly available to program personnel in the cloud server. The government/program enterprises must plan for and ensure the endurance of the central data storage across the system lifecycle. In this process, there will be a need to hire and gradually shift toward a more data and IT savvy workforce, who must manage the scale and complexity of the central data storage. Commercial advances in artificial intelligence, big data, and machine learning should enable tool development to help manage the AST and data store.

Digital model and data validation will be a concern. This should lead to a rethinking of how development and operational testing is done in the DoD. Design Models and data validated by test data will become part of the data entered and extracted from the central data store. Shared access to validated models and test data will enable increased trust between the systems engineering community and the operators in the warfighter community, leading to acceptance of new practices.

The benefit to central data storage is a single portal to all program information. The outcome will be everything is on the program office desktops when needed. This will make it much easier to find and use data, and a consensus among early adopters of DE is that this will significantly reduce or eliminate design escapes, or defects that persist to later lifecycle stages. Over time this benefit will be critical to program office staff in their struggle to better manage system complexity. The ease of access to program data should also improve agility, with direct benefit for the warfighter.

A critical aspect of the AST is the increasing use of model-based engineering. Digital models will be built and used by future system engineers, who will take on the primary role of data and model evolution as well as version control of the central data store. Although this is not new in systems engineering, it will become the primary role. Digital models also support knowledge translation between disciplines and enterprises for systems engineers.

As programs move toward operations and sustainment, program offices become responsible for system updates. Digital models will define and control interoperability across future systems. This, along with good decisions in the procurement of digital technical data, will enable competition in future system updates, spurring much needed innovation. Good system architectures with good system model and data baselines will become essential to managing the realm of the possible for the warfighter and their systems.

3.4 SYSTEMIGRAM 2: DIGITAL ENGINEERING TO INFORM ENTERPRISE AND PROGRAM DECISION MAKING

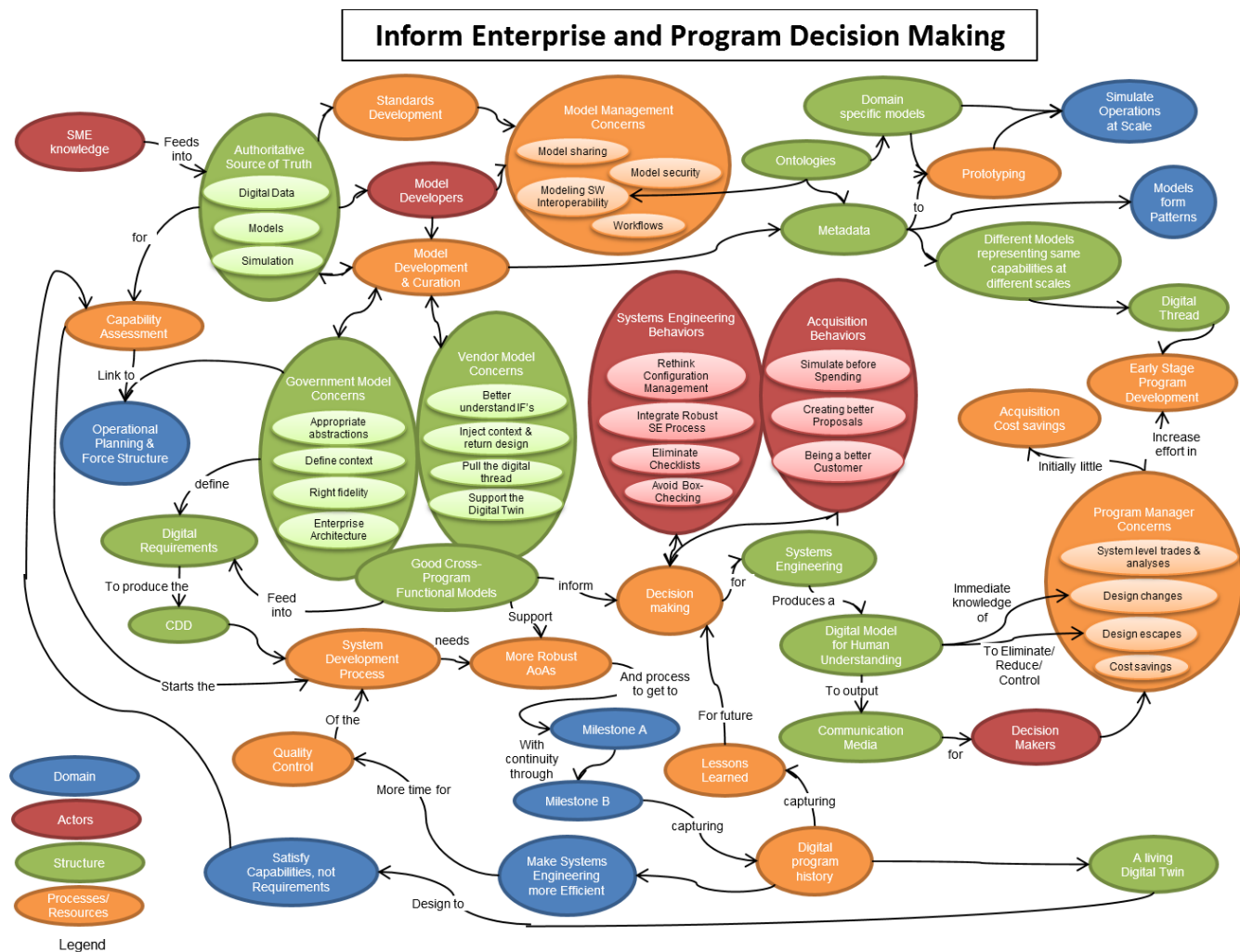


Figure 4. Systemigram 2: Inform Enterprise and Program Decision Making

Given the widespread transformation to Digital Engineering, there are questions over how will it be used to inform enterprise and program decision making. The Authoritative Source of Truth (AST) will be a core component as program data, information, and knowledge shifts from inaccessible documents and stove-piped program offices to collaborative access in the AST.

Subject Matter Expert (SME) knowledge will be fed into the AST in the form of digital data, models, and simulations to be used for capability assessments linked to operational planning and force structure. Model developers will need to focus on model development and curation across a large set of government and contractor models. Previously these may have been standalone and "stove-piped" between model development teams. Model developers will need to address new model management concerns such as model interoperability and model sharing, modeling software tool interoperability, new modeling workflows, and model access and security concerns. Government and contractor teams will need to cooperate on model development and curation. Government will be primarily concerned with enterprise architecture definition, leading to digital representation of CONOPS and requirements. Government models will help define the context for the systems of systems more explicitly, and a learning process through pathfinders will help settle on appropriate levels of abstraction and the right level of fidelity for government developed models. Contractors will inject their models into the government context and

jointly establish better upfront understanding of interfaces. The contractor will have primary responsibility for “pulling the digital thread” across the development effort, and capturing a “living digital twin” from the design to support the full program lifecycle. This should result in good cross-program functional models to support more robust analysis of alternatives (AoAs), feed into digital requirements baselines, and inform decision making. Future digital requirements will generate program Capability Definition Documents (CDDs) and other upfront program documentation.

The AST should also be used for government capability assessment processes that will link the government models to defense operational planning and force structure assessment. The link between the AST and the capability assessment process should carry forward into digital CDDs to start the system development process. This link and good program functional models will support a recognized need for more robust AoAs and process that carry the AST through Milestone A with continuity to Milestone B. The continuous capture of digital program history is essential for creation of the living Digital Twin. The DE community consensus is that this will make systems engineering more efficient, giving systems engineers more time for quality control of the system development process.

Good cross program functional models will inform decision making for systems engineering teams. Data and model artifacts extracted from the AST will produce a unique set of digital model artifacts targeted at improved human understanding of the program technical data. This will be output to communication media for decision makers who are addressing typical program management concerns such as system level trades and analyses, requirements and design changes, and management of design escapes and defects. A key benefit of this “digital model for human understanding” will be immediate awareness of design changes and an opportunity to eliminate, reduce, or control design escapes. The long term outcome should be program lifecycle cost savings and shortened program schedules. Of note in this process is that program managers should expect little acquisition cost savings as these will be realized later in the lifecycle. While an increase in effort in early stage program programs development with upfront investment will be needed, this should accelerate the overall development schedule.

This approach to knowledge sharing and decision making should gradually change the behaviors of systems engineers and acquisition professionals. DE is all about good systems engineering and should lead programs to integrate a more robust SE process. The “box-checking” mentality that pervades much of SE practice should be avoided and checklists eliminated in favor of the digital model for human understanding. In the long term, programs will rethink configuration management practices which today produce static and unsustainable artifacts. In the acquisition community, there should be an increase in simulation based acquisition, or “simulate before spending,” leading to the creation of better proposals and allowing the program office acquisition professionals to “be a better customer.”

The process of model development and creation and model interoperability will produce new outcomes across programs. Model curation will produce metamodels and metadata that design and decision making across the engineering disciplines. Metamodels will be enabled by the development of standard ontologies that support model sharing and by standard abstractions, leading to more efficient domain specific model development (and languages) that ease reuse across programs. One outcome will be improved models and data supporting simulation of operations at larger scales. Shared metadata and domain specific models will also be used to inform more and better prototypes. Over time different models representing the same capabilities at different scales will make up the digital thread, feeding improved knowledge into early stage program development. The creation of a living digital twin and associated models can also lead to designs and updates that better satisfy capability needs, not just requirements, feeding back into government capability assessments.

3.5 SYSTEMIGRAM 3: THE DIGITAL ENGINEERING INFRASTRUCTURE

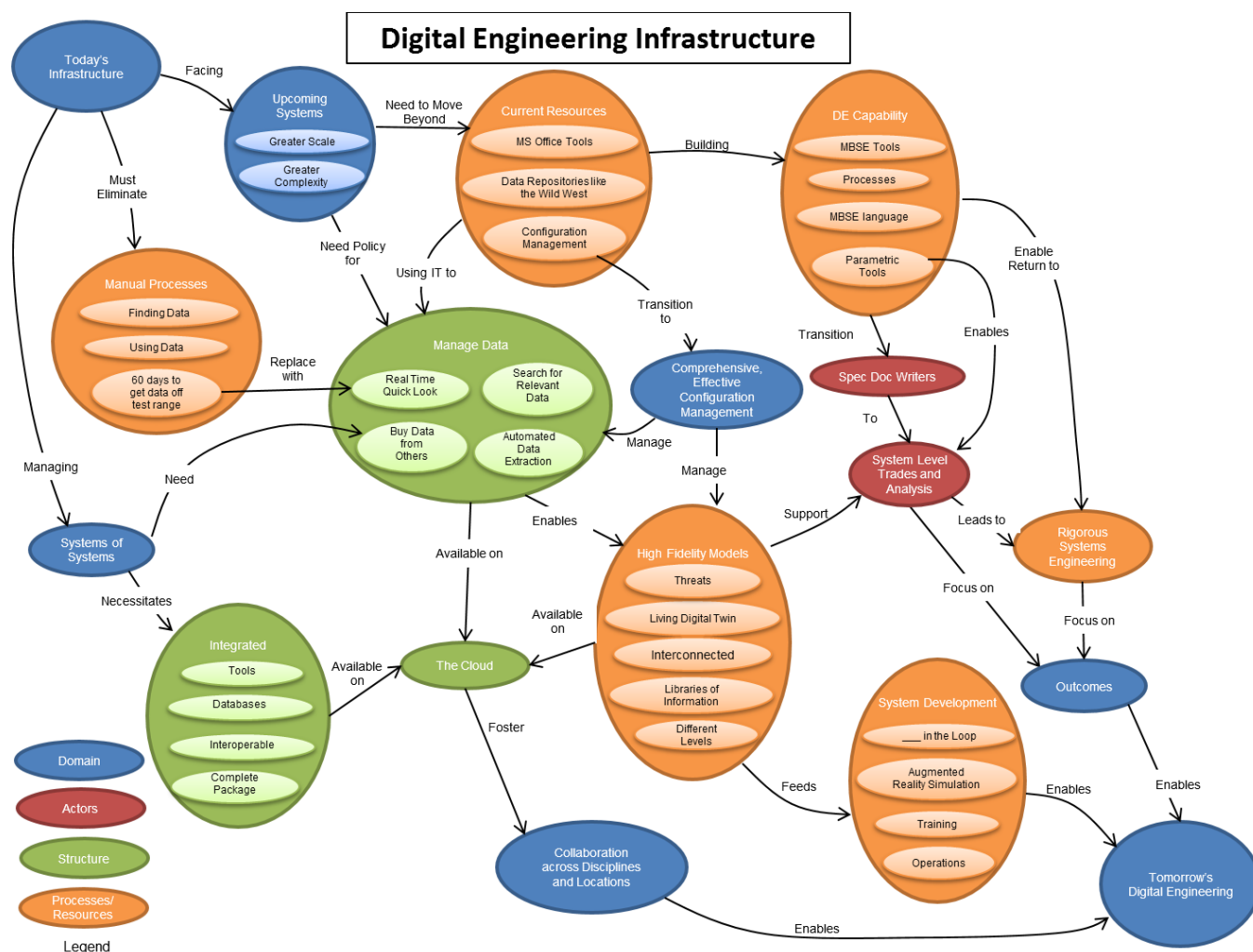


Figure 5. Systemigram 3: Digital Engineering Infrastructure

Today's acquisition engineering infrastructure is challenged by projects of increasing scale and complexity. Engineering work is built upon Microsoft Office tools, which are often inadequate for larger complex programs. Furthermore, data repositories are scattered and inaccessible, with no way to validate the quality or accuracy of their contents. Finding the data is a manual process and formats vary with every data source. Configuration management is essentially an ad hoc and informal process, and most of the time it does not exist at all. It often takes sixty days to get test data from a test range.

Engineers need IT communications and database infrastructure that search across repositories for relevant data, automatically extract the data in a useful form, and provide a real-time quick look at test data while it is still at the range. This will not only require hardware and software tools beyond what is currently installed, it will also require new policy to make data available and standardize access and format. In addition, a comprehensive, effective configuration management system is needed to identify current data and old data, and to establish the pedigree of the data.

This improved infrastructure will enable a substantial and necessary improvement in the quality and fidelity of models that support acquisition engineering. Multi-level models will describe and document the system design at various levels of detail. High fidelity models of the threat will be essential for effective weapon systems. The most

significant improvement will likely be the interconnection of all models, wherein results from one analysis can flow seamlessly into another simulation. All of the models will draw on curated libraries of information, enabling updates to propagate immediately across all the engineering models. Digital twins will live amongst the models of test articles and designed components and systems.

These models will be used to support testing, including: software in the loop, hardware in the loop, human in the loop and so on. High fidelity models will support augmented reality simulations of the designed system on the battlefield. The models will continue to be maintained after Initial Operational Capability (IOC) to support training and operations.

Today, the acquisition system is struggling to manage SoS. To do this successfully, it will require integrated tools and databases that support all the subsidiary systems simultaneously. Of course, the DoD does not own complete data rights to all these systems. Therefore, data must be purchased from others to populate the integrated databases. Before the systems can be designed to be interoperable, the tools and databases that support their design must be interoperable. All the interoperable tools and data should be available on the engineer's desktop as a complete package.

To replace current desktops that are centered on Microsoft Office tools and happenstance data sources, we need systems engineers to move to Model-Based Systems Engineering Tools, parametric tools and Digital Engineering processes. Systems engineers should transition from writers of specification documents to decision makers and analysts who conduct system level trade studies and system level analyses. These trades and analyses will be supported by the high-fidelity models supported by curated databases that are configuration managed to stay current with the project.

The data, tools, and models should be available to every engineer who needs them through the cloud. This will enable collaboration across disciplines and across locations. Improvement occurs with desktop tools and capabilities, MBSE and Digital Engineering, and elevation of the role of the systems engineer to analyst and decision maker instead of document manager—all of these factors will enable a return to rigorous systems engineering that focuses on outcomes instead of process. These infrastructure changes will lead to the Digital Engineering environment of tomorrow.

3.6 SYSTEMIGRAM 4: TECHNICAL INNOVATIONS TO IMPROVE ENGINEERING PRACTICES

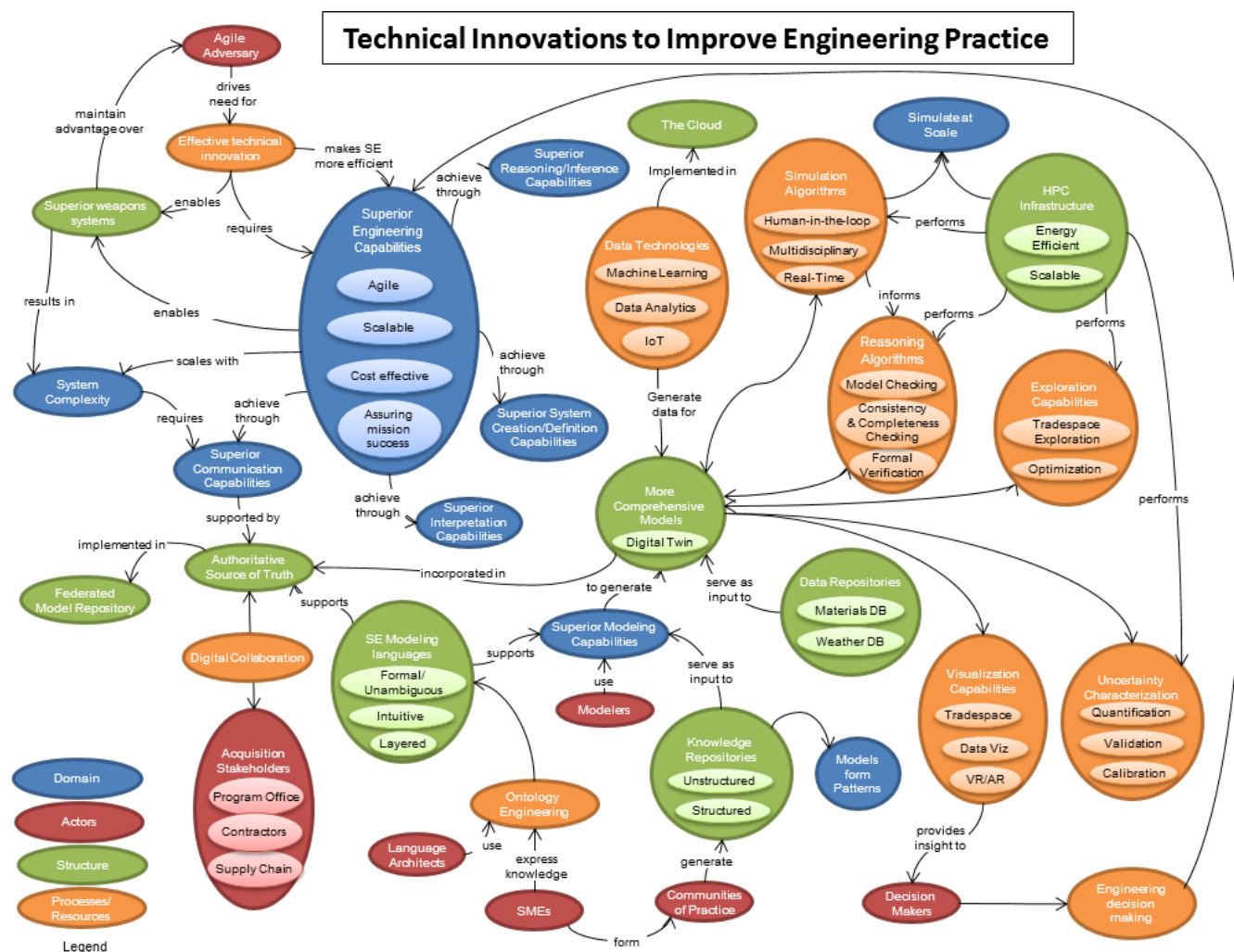


Figure 6. Systemigram 4: Technical Innovations to Improve Engineering Practice

An important aspect of the transformation towards Digital Engineering is the need for Technical Innovation to support and enable improved engineering practices. This need is driven by an agile adversary who continually innovates its capabilities. The US can maintain a strategic advantage over the adversary only by innovating more effectively and creating superior military capabilities. To keep pace with — or preferably outpace — the adversary’s rate of innovation, we must invest in the improvement of engineering practices that enable the efficient and effective development of evermore complex military systems. This is where Digital Engineering plays a role—it will allow the US to innovate more effectively by making systems engineering more efficient. It promises to provide superior engineering capabilities that are more agile and scale to larger and more complex systems, capabilities that are cost effective and result in systems that assure mission success.

Superiority in engineering capabilities and practices can be achieved through innovation in several technical areas:

- Communication capabilities,
- Capabilities to support the definition of systems and the creation of models
- Reasoning and inference capabilities, and
- Capabilities to support the interpretation of and decision making based on the analysis results.

These technical areas are discussed in more detail below.

- 1) *Superior Communication Capabilities:* As military systems become increasingly complex, their successful development involves an increasing number of specialists to cover both the breadth and depth of technical knowledge required. Digital engineering must create superior communication capabilities to allow this large number of stakeholders to communicate efficiently and effectively. At the core of this communication capability is the authoritative source of truth, implemented in a federated model repository. It is through this authoritative source of truth that all the acquisition stakeholders can communicate digitally and maintain a common view on the state of the system throughout its lifecycle. To enable unambiguous communications, the authoritative source of truth requires the support of layered, formal, unambiguous but intuitive systems engineering modeling languages. The development of these languages, in turn, requires language architects and subject-matter experts to collaborate on the engineering of a formal ontology for the systems engineering domain.
- 2) *Superior Modeling Capabilities:* Besides the development and use of systems engineering languages for communication, the languages need to be supported by superior modeling capabilities (i.e., methods and tools for practicing systems engineers) for the definition and modeling of military systems. Creating these models efficiently and effectively can be achieved by capturing structured and unstructured domain knowledge in knowledge repositories developed by communities of practice. Besides serving as a knowledge retention mechanism, the domain knowledge in the repositories often forms model patterns that can be reused, combined and configured into larger models, significantly improving overall modeling efficiency. Such improved modeling capabilities make it economically feasible to develop more comprehensive and detailed models — an important step towards the concept of a digital twin. In addition to the knowledge repositories, several data repositories also serve as inputs to these comprehensive digital twins.
- 3) *Superior reasoning and inference capabilities.* In addition to the specification of the system, the digital twin also incorporates analysis results obtained through the use of data technologies, simulations, or other forms of reasoning and inference. Increasingly, simulation models are informed and calibrated by data collected throughout the systems' lifecycles. Tapping into the IoT-capabilities (Internet of Things), combined with data analytics and machine learning, all implemented in the Cloud, allows analysts to generate increasingly accurate, predictive models for design concepts during development, or for specific, individual systems during operation. Increasingly sophisticated simulation algorithms will allow systems to be simulated at scale, from multiple, integrated disciplinary perspectives, potentially in real-time, with humans in the loop. Such large scale simulation are enabled by energy-efficient, scalable high-performance computing (HPC) infrastructure. Besides simulation, HPC also enables other forms of reasoning such as model checking, formal verification, and consistency and completeness checking. Formal verification methods are particularly important in scenarios where simulation is ineffective (e.g., in the case of rare events or adversarial agents). Finally, it is expected that simulation capabilities combined with HPC capabilities will not only be used for final analysis of the selected systems alternative, but for a broad exploration of the tradespace, comparing millions of architectural alternatives in search for the one providing the best system-level tradeoffs.
- 4) *Superior interpretation capabilities.* A final aspect of a strategy towards improving current engineering practices targets improving the visualization and interpretation of engineering data, and improving its use in support of decision making. To make good decisions about complex engineered systems or corresponding acquisition strategies, decision makers need interactive visualization capabilities for presenting tradespace analysis results or data visualization of detailed engineering, economic and tactical analyses. In addition, to properly take risk into account, uncertainty characterization are needed, based on uncertainty quantification of validated, calibrated models.

The combination of all four areas of technical innovation outlined above will result in improved engineering decision making, superior engineering capabilities, and ultimately, superior weapons systems that maintain our strategic advantage over future adversaries.

3.7 SYSTEMIGRAM 5: CHANGING WORKFORCE AND CULTURE

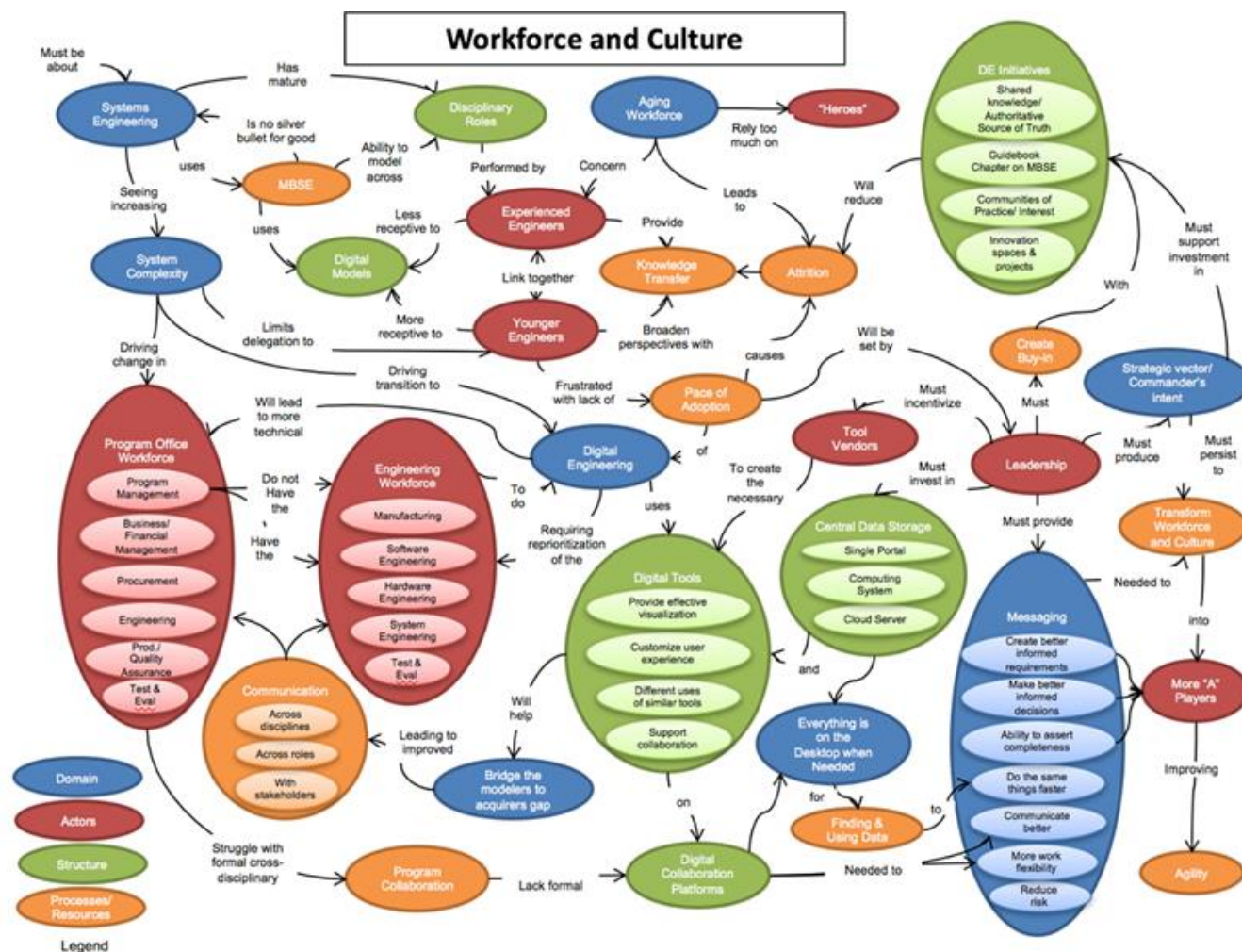


Figure 7. Systemigram 5: Workforce and Culture.

Much of the discussions around digital thread and digital engineering focuses on the technological and modeling aspects. While those are integral to the changing dynamics and processes, often overlooked is the human role and associated changes and how it will shift and might change over time, as the broader system seeks to become more agile.

Most stakeholders and experts do agree there is a cultural change at play, along with needs for the workforce to adapt and change with the broader trends at play as well. There are divergences in perspective in regards to what this might look like, the change in the “old guard” to “new guard”, whether or not there are workforce capabilities and the “talent” will look like. DE is a cultural change in and of itself. There are the new tools which bring in digital natives and will be a merger of new technology and existing experience. As such, the workforce shift will be substantial. There will be big struggles to learn new ways. The goal is having the models to feed the decision processes, which requires training of modelers and a new breed of decision makers. However, it is a challenge to get a large group of people to change. Culture change is not done without resistance or done overnight. There is an extraordinary advantage to maintain the status quo and temptation to “do it like how we did last time”. Culture change is organizationally dependent and unchangeable.

One of the bigger points of diversion amongst stakeholders is whether or not there is a workforce in place to grapple with the changes at play, and if so, whether there are capabilities to address the changes. On the one hand, DE is

done today often times without the realization that is being applied. People who do models do it without thinking about it. However, there lacks the process and culture to bring together the emerging digital natives with grizzled veterans and their domain knowledge.

On the other hand, there is the belief that much of the workforce is an aged workforce that looks back at the way things were done rather than looking to the future. The younger group coming in also has shortfalls. The younger workforce is more skilled in a single discipline rather than a broad perspective. There needs to be an effort to better train the younger workforce to oversee multiple different domains to provide a more robust understanding of digital environment. However, bureaucracy and paperwork make it hard to train due to time constraints. Additionally, there is not enough money or time to train older workforce to train them how to use new tools as well.

This squeeze on resources also impacts the focus on SE, as discipline workforces are less and less SE focused and system implications. Labor is expensive and systems are expensive to implement. There are no expectations to think about larger system aspects from the onset. Hiring managers are worried about finding MBSE workers, but there should be more of an effort place finding systems engineers.

This reflects a broader tension between the “old guard” and “new guard”. The steep learning curve and new tools that traditional SE don’t feel comfortable with creates tensions as organizations try to create enhanced capabilities and more agility. Receptivity to modeling is inversely proportional to age. A lot of the innovative stuff is early career - modeling savvy, IT savvy, digital repositories versus paper. These are wired into recent graduates, as such, there will be a gradual aging out process. It is not forced that every engineer be a SysML professional; however, it is encouraged that most at least be a student of it so can speak knowledgeably about adoption. While this is mindful of the “older” generation, the younger generation are frustrated that the move to digital in general is not happening fast enough. This creates a possibility that they might get lost over time. There is a need to instantiate workflow processes - not just the workflow but the policy on the data with it. Still, SE is not about pushing buttons or drawing pretty pictures. A SE should also be a systems thinker, and understand system level analysis and impact. They should be able to understand the broader impact of design changes. It comes down to systems thinking at the end of the day. The key to a good SE, is experience. You can teach someone fundamentals, but you can’t make them one. They need the experience.

Another aspect is that experienced system engineers don’t know how to model, and modelers don’t have system engineer experience. What is the pathway that all system engineers know how to model? There are separate study managers, principle investigators, and modeler roles. Much needs to change before organizations get fully digitized. There are challenges on how to combine the varying skillset levels of the engineers and how to team them up. Need to develop a cadre of modelers who can help stand up MBSE in the projects. We can’t expect all of the SE’s in the physical domain to adopt MBSE.

Digital work environment

With DE, digital collaboration is a key enabler. Whether it be communication devices, like smart phones or iPads, or the availability of data with the cloud, there is a distinct ability to integrate data on the cloud. The difference in communications tools is huge and instantly available information. This also helps with collaboration. This will impact the workforce and culture as well. Workforce priorities might change; however, are they grown in house? Do they immediately come in as a system engineer? Is that our next generation of lead systems engineers? SE and SW engineering disciplines will become a key part of the transformation.

If there is a DE environment, what will it look like? Will there be more telework options? For instance, talent could be spread out more evenly, but currently, the government or defense doesn’t have flexible policies for this. In a digital environment, there could be segmented work down into a digital model. DE might make the acquisition

workforce more flexible and distributed. Vendors are doing design virtually across multiple teams and locations. This can result in critical cost reduction. If there is some probability of a success with a reduced cost, this is a big win. There will no longer be a need for as many “heroes” working 80 hour weeks and sacrificing their lives for a project or program. This energy and effort can be diverted in other places.

Some organizations support a workforce that employees people to solely understand why we need policy and what it looks like, it drives the paradigm of letting the workforce find out how they use the models and the workforce drives policy so they aren’t over constrained. There are contrasting policy models, some people use policy as checklist and that makes you a good system engineer. While others don’t worry about policy too much and focus on what needs to be produced and do we need all of the products that policy says. Workforce needs to understand which policy to efficiently use. In the policy realm, a special topics chapter on MBSE in the guidebooks would help. Governance is another big piece in this that we need to figure out. Governance is needed at multiple levels. That will have to involve signaling to everyone else.

Overall, in 25 years, SEs will recognize that there are very few problems we haven’t seen before at some level of abstraction. A lot of people think they are the first person to face that problem. Finding the correct abstraction language will let us know what problem we are facing. We are all solving the same problem at the fundamental level. The tools can start to focus on providing templates for problems we have solved before.

3.8 SYSTEMIGRAM VALIDATION PROCESS

Systemigrams are by their nature stories that are assembled and told by the research team. They are subject to biases of the stakeholders interviewed and also by biases of the research team. Care is taken in the interview process to build a diversity of perspectives from a selected stakeholder group that is assessed to represent as many aspects of the system as possible. Researcher biases are reduced by using the words of the interviewees, not the research team, and the process of diagramming the systemigram also help to build unbiased models. However they are snapshots in time based on knowledge of the interviewees and it is wise to thoroughly review the work with sponsors and stakeholders and update them over time as the change process progresses.

The systemigrams were reviewed in a workshop format by the sponsor team chartered to enact the DE strategy. In this process the research team walks through their stories using the diagrams and the review team discusses, agrees with, or suggests changes in the models. After the review the narratives and diagrams are updated with their insights. The systemigrams in this report have at this point been validated by the research team and the sponsor team, but should continue to be discussed with the stakeholder communities until there is broader consensus that they accurately reflect the desired strategy and future.

The systemigrams in this report will continue to be discussed across the stakeholder community via the following:

1. Conference presentations and technical papers;
2. Use of selected artifacts in digital engineering working groups;
3. Direct presentation and review with the interviewees, as available;
4. Broader validation with selected stakeholders outside of the research team, sponsor team, and interviewees.

4 Enterprise Innovation: the Three Horizons of Change

In order to make plans and strategies for the future, we have to think of what the future will look like. However, this is much harder than many can conceptualize, especially when considering the complexities of an enterprise like DoD acquisition. In light of these characteristics, the research project used the Three Horizons Framework [12] to give us a deeper understanding of the significance of what we usually call short, medium, and long-term futures. Attention to the three horizons always exists in the present moment, and our evidence about the future is rooted in how people (including ourselves) are behaving now and see the future.

The framework is based on the observation that business, technologies, political policies, and entire communities exhibit life cycle of initiation, growth, peak performance, decline, and more. These cycles can be viewed as waves of change in which a dominant form is eventually overtaken and displaced by another. These displacements are gradual but in can appear to be quite abrupt. A closer look reveals that these waves are also going on simultaneously on different scales, changing their place between the foreground and background of our awareness over time. This is not easy to see unless we appreciate the qualitative differences between the waves. A key difference between the Three Horizons framework and other strategic foresight methods is that it allows the selection of futures to be aspirational – instead of focused up front on strategy or intentionally broad. It tunes our awareness toward the signals of change that align with our aspirations, without the pressure of correctness or accuracy. The purpose of the tool is not to reach agreement on possible futures, rather to gather a large set of anecdotes on current, near-term, and far-term states from the participants. Initially use of the framework is to identify future dilemmas and emerging interactions to help populate a system map. Three Horizons is a way of working with transformational change, drawing attention towards systemic patterns rather than individual events, or unexamined trends; it frames the discussion in terms of the shift from the established patterns of the first horizon to the emergence of new patterns in the third, via the transition activity of the second. Figure 8 provides a description of each of the three horizons and a visual depiction of the map.

A Three Horizons workshop was conducted with the project sponsors in order to gain insight in how this stakeholder set views the innovation paths for DE transformation. The facilitation was “seeded” with a set of anecdotes in each horizon that were captured from the interview narratives. Figure 9 shows the final map after facilitation.

There were a number of themes from this facilitation that informed the systemigram development process. A primary emergent theme is the increasing complexity of defense systems and the inability to manage them further without new processes and paradigms.

THREE HORIZONS FRAMEWORK

- ❖ A way to look at the processes of change and encourages us to see deeper patterns of systemic change beneath surface events.
- ❖ A way to make the future accessible in the present, depicted in the form of the intents and actions, which are bringing it about.
- ❖ A way to bring all the voices of continuity and change into play as part of the discussion, as expressed in their intent towards the patterns.

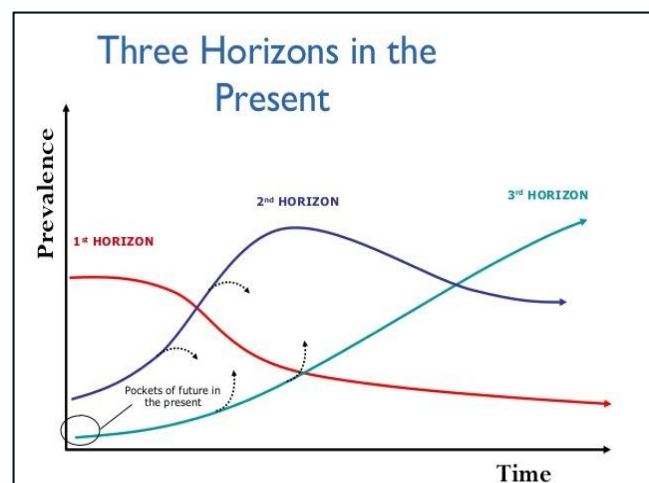


Figure 8. Three Horizons Pathways.
(Source: International Futures Forum)

❖ HORIZON 1

The first horizon describes the current way of doing things, and the way we can expect it to change if we all keep behaving in the ways we are used to. H1 systems are what we all depend on to get things done in the world. Innovation and change in our H1 systems is happening, but it is about sustaining and extending the way things are done now in a planned and orderly way; uncertainties and risks are to be eliminated or prepared for – the lights must be kept on. Nothing lasts forever, and over time, we inevitably find that our H1 ways of doing things are falling short – no longer meeting expectations, failing to move towards new opportunities, or out of step with emerging conditions.

❖ HORIZON 2

The second horizon is the transition and transformation zone of emerging innovations that are responding to the shortcomings of the first horizon and anticipating the possibilities of the third horizon. H2 innovations seem very similar to your current products and services, and the overpowering temptation is to use the same metrics to assess their success. However, because these ideas are new, it takes time to get them configured effectively. This means that if you treat H2-oriented innovations just like H1-oriented innovations, you are likely to abandon them too quickly because it will seem like they are not performing well. You have to figure out a way to ring fence H2 innovation efforts.

❖ HORIZON 3

The third horizon is the future system. It spurs reflection and capturing of new ways of living and working that will fit better with emerging need and opportunity. H3 change is transformative, bringing a new pattern into existence that is beyond the reach of the H1 system. There will be many competing visions of the future and early pioneers are likely to look quite unrealistic – and some of them are.

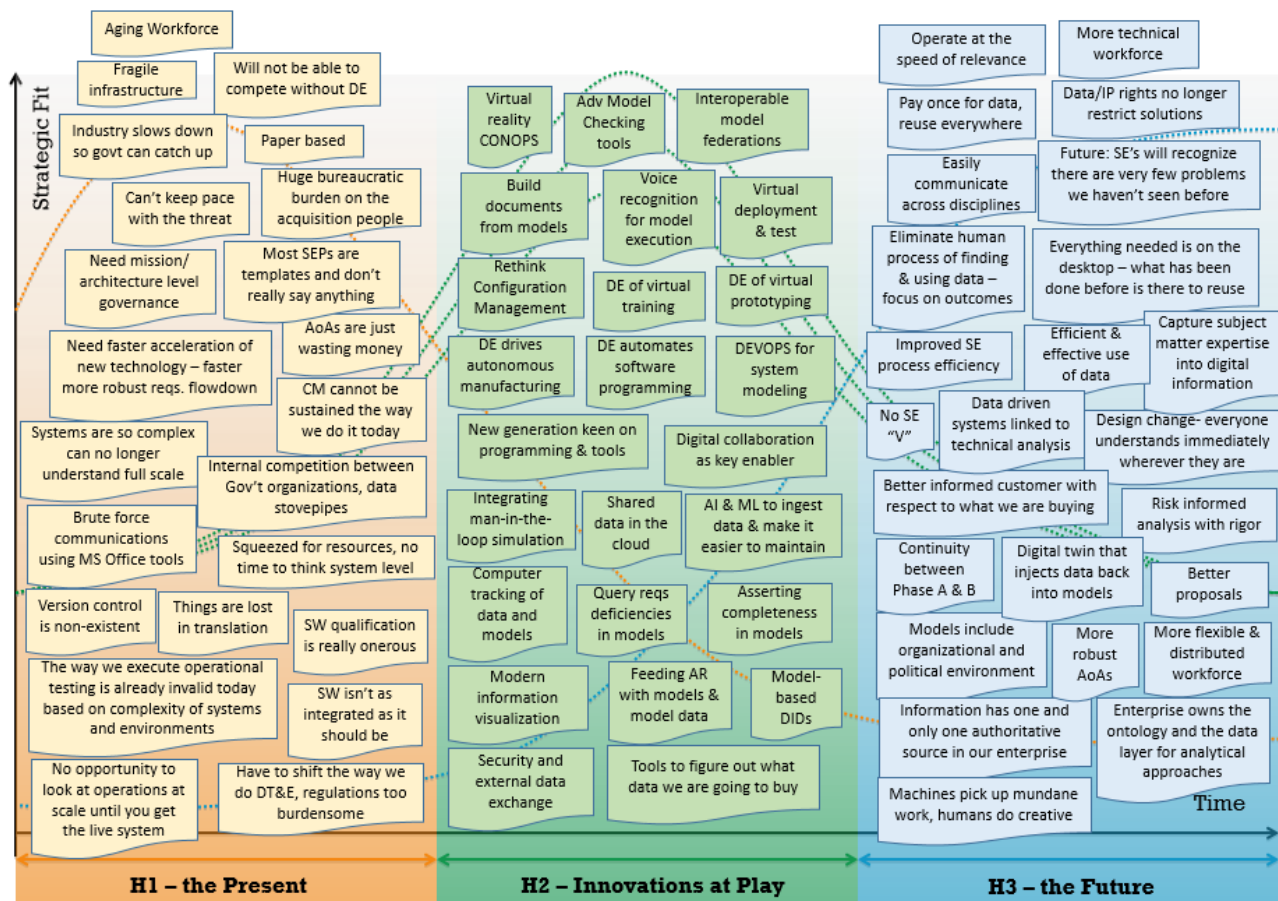
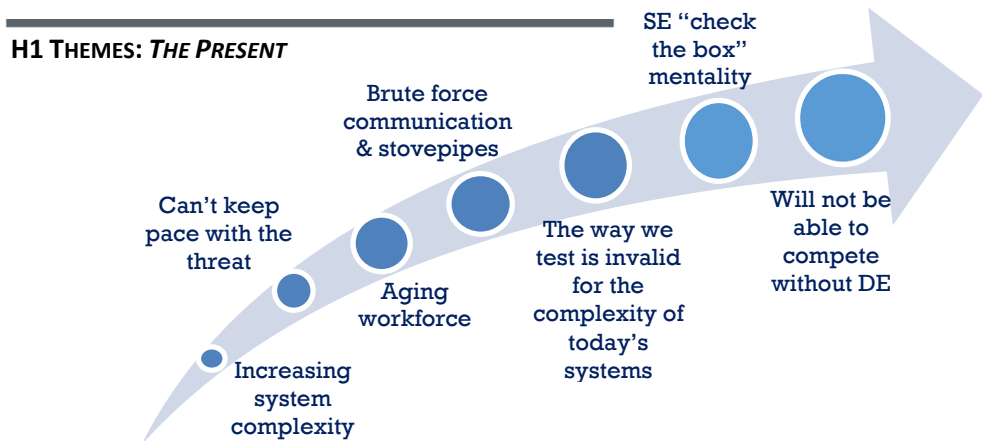


Figure 9. Final Three Horizons Map from the Facilitation.

Beginning with Horizon 1 (H1), the group identified numerous unsustainable practices centered on increasing complexity of today's systems and inability to keep pace with the threat. There is an understanding that digital engineering is the next organizational efficiency driver and the DoD must keep pace or risk ability to compete. Operational test is a



particular area needing transition, as the complexity of modern systems are already overwhelming or ability to verify and validate performance using traditional processes. Regulatory burdens are immense and must be reevaluated in a digital environment. The community must rethink how configuration management is maintained in a SoS construct. DE is about good systems engineering, and the trap of checklists and check the box artifacts must be eliminated. There is hope that DE can also accelerate adoption of new technology, prototyping, and transition. There is recognition that new means for communications across disciplines and programs must be adopted. DE can address a number of these unsustainable practices, and the feel is that the landscape has opened for change.

Next, the group discussed Horizon 3 (H3), which captured the future aspirations, emerging practices, and new systems of governance, education, and technology that might support solutions to the problem. A primary high level aspiration is to transition to an acquisition process that operates "at the speed of relevance," improving agility and matching or exceeding the speed of the threat. How will DE support this? The group envisioned a future where

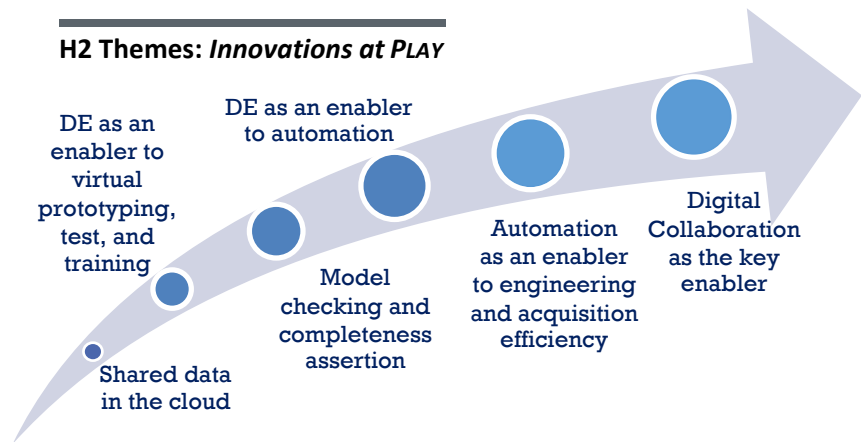
H3 THEMES: *The Future*



collaboration across disciplines, across, programs, and between government and contractor becomes the norm. DE provides all needed information on the desktop when needed, leading to better decisions, automation of the process of searching for data, automation of mundane work enabling time for human creativity, and transfer of knowledge across the system lifecycle. In this future, the acquisition professional becomes much better informed, a better buyer, and increasingly more technical and data savvy. Data becomes a shared program commodity, enabling immediate shared knowledge of change, more robust analyses, and improved means to buy and use data. This will not be easy, as the government enterprise must transition to a data driven entity that owns the overall ontology and data layer for shared models, governs one and only one authoritative source of truth, and effectively configuration manages trusted data and model sets.

The facilitation then moved on to consider the innovations at play in Horizon 2 (H2). In H2 one looks for signals of H3 in the present, and considers how those will play out to reach the aspirations of the H3 future. The idea of engineering in the cloud pervades the innovation space, leading to digital collaboration as the key enabler for the H3 future. DE as an enabler for other engineering and acquisition lifecycle processes provided some insight into the value of DE, as it

will maintain data and models that directly feed virtual prototyping, test, and training activities. DE should also become an enabler to design and manufacturing automation, and early “manufacturing 4.0” initiatives are proving its value. Another thread was automation as an enabler to engineering and acquisition process efficiency, as machine learning and data-driven tools should automate many of today’s manual processes. These will all be accompanied by new innovation in data visualization, creating the environment for digital collaboration. The H2 view in this process was informative, but as is often the case in a first iteration of the H2 framework, too focused on incremental improvement of today’s world and lacking truly transformative views. Repeating this facilitation in future research, with a broad community of government and industry, is recommended.



The following examples of innovation needs stood out in the interview narratives, systemigrams, and Three Horizons facilitation:

- Methods, processes, and tools that improve the way we develop and manage enterprise architectures, conduct analyses at the SoS level, and execute more robust AoAs. Needs include the ability to simulate the to-be system at scale and at varying abstraction levels, continued advances in High Performance Computing to enable these simulations, reasoning algorithms that automate the verification of models and simulations at much larger scales than today, layered SE modeling languages and standards, standardization of ontologies and domain languages reflecting DoD systems, and efficient ways to implement data and model federations that link to the AST.
- A need to reinvent the way we do configuration management today. The complexity of today’s systems-of-systems exceeds the capability of existing configuration management methods, processes, and tools. Future configuration management processes must be much more dynamic and provide better support for multiple concurrent configurations. The Development Operations (DevOps) trends in the present provide an operational model for the future, but must be scaled to a much broader set of methods and tools that in use today.
- Big data automation of engineering data is needed to help manage the scale and complexity of AST and aid in finding and using data for decision making.
- Automation of the digital twin to continuously update the system’s digital history will be game-changing. The concept of instrumenting a system in order to keep its models up to date is beginning to find use in the building information management field, and should have application to models in the AST.

5 Innovation System Analysis

The analysis to this point has served to define that landscape and the potential innovation pathways that may drive it. To make the analysis actionable, the research must begin to define a systemic innovation model. This cannot look at solutions, which will defy prediction. Instead it must look at the language that defines the new landscape, the key actors who will instigate or oppose change, the enabler or barriers to change as it proceeds, and metrics that follow leading and long-term indicators of change. This section captures the initial results of an innovation system analysis. The research methods view this analysis through the lens of transformative innovation, using a three-systems model treats the system of interest and the innovation system as two separate agents that must come together to produce transformative change.

5.1 METHODS BACKGROUND: VIEWING TRANSFORMATIVE INNOVATION AS A THREE-SYSTEMS PROCESS

Today we often associate “innovation” with “technological innovation.” In truth, innovation constitutes a combination of social factors, processes, governance and management issues, and sometimes technologies that, when integrated, offer new value or utility. Transformative change occurs when a series of disruptive innovations (e.g., products, processes) are diffused and gain adoption across a system such that the system is wholly changed over time. These innovations, however, do not offer value in isolation of context. Rather, it is often the system in which innovation is deployed together with the system from which innovation arises that determines whether an innovation is absorbed, adopted, and ultimately appreciated as a catalyst of broader social change. Using a systems perspective allows for these many important features to be considered.

Figure 10 depicts the process of systemic change in a systems landscape. This view derives from a body of work known as “Transition Management” as well as related work on social innovation impact [13] [14]. An innovation transformation is often thought of in a product-centric view where individual products are designed, piloted, sustained, and eventually scaled to disrupt a current (Horizon 1) system. Real innovation seldom happens this way. Instead it is a series of innovations that play into a system landscape that has become open to change (such as digitizing DoD acquisition) and eventual link together to produce a new system landscape. In understanding this transformation process one must look at: 1) Changes in the system landscape that may signal time for change;

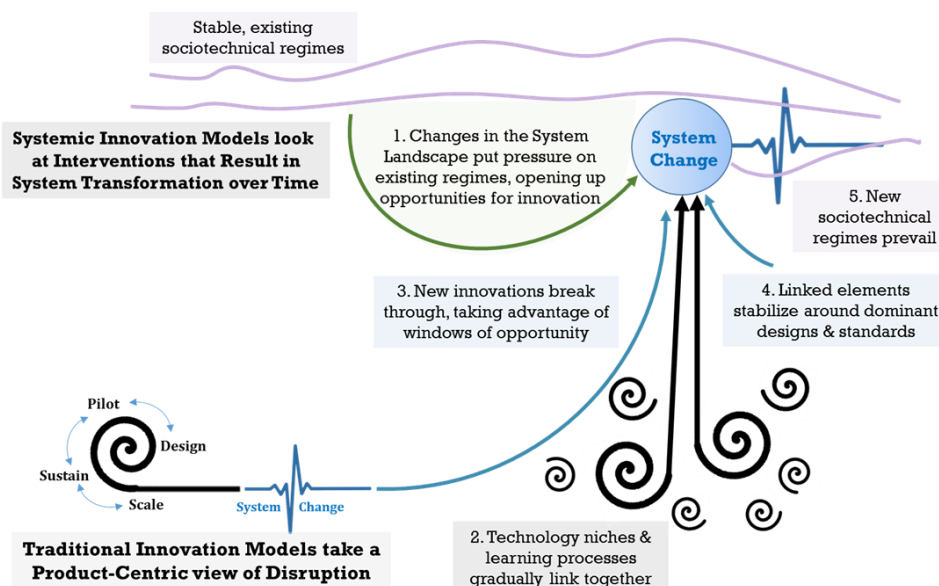


Figure 10. Innovation Driven Transition.

2-4) Areas of innovation that might link together to change the system landscape, and 5) how these might come together to produce a new regime which is the desired aspiration or goal.

An outcome of the data collection and conceptual modeling activities is a holistic view of the enterprise in systems-of-systems terms. The resulting ESoS model captures three perspectives which in this process is referred to as a “three systems model.” We view the enterprise system and its sociotechnical context in a model that represents the system as a set of innovations that create change to the larger context in order to improve a situation. Figure 11 shows the degrees of overlap and separation among the three distinct systems that make-up the three systems model. This view has been inspired and adapted from Larsen’s “universal mental model” of a system [14]. Each system represents a complex environment of interacting elements, but at potentially different abstraction levels. The relevance of each system are explained below.

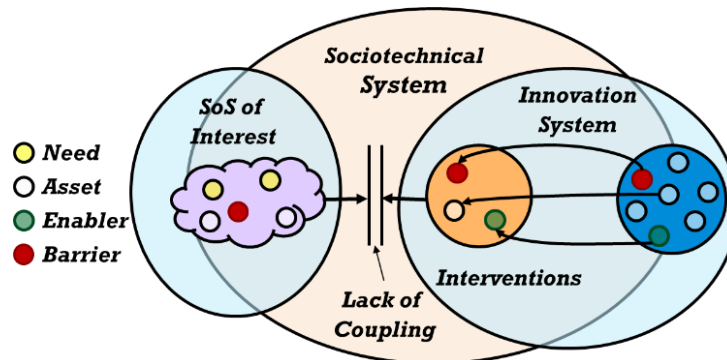


Figure 11. The Three Systems Model.

System 1: The SoS of Interest. The context for introducing a new project is always an existing system-of-systems (SoS) that contains technology, policy, economics, social, and environmental drivers. Defining the characteristics of the SoS of interest provides insight specifically into the needs or requirements context of the three systems model. Tools that clarify the existing system features and current state or situation define the problems in the system for which innovative solutions would emerge. When describing the system of interest it is important to consider the situational as well as the structural views.

System 2: The Innovation System. Most enterprise change analyses focus on structural and behavioral aspects of the solution, so the temporal aspects of evolution must be assessed. System innovation occurs in a dynamic system shaped by complex interactions among the stakeholders, which can include research, industry, community, government, and many other innovation system actors. How these actors will enact change cannot be predicted, but the likely innovation impact areas can be identified. Given this, specific actions to enable innovation and eliminating barriers to innovation. A strategic investment strategy should focus on enablers and barriers instead of solutions (which are tactical in a transformation arena).

System 3: The Sociotechnical System. The sociotechnical system is where the SoS of interest and innovation system come together. This view supports analyses of the broader decision context. This context or “landscape” includes the SoS of Interest but also the aspects of the innovation system that might act on the SoS. This could drive assessment beyond a specific geographic boundaries, district, or enterprise layer, for instance, in which the context is meant to be addressed. The previous analysis of context and resulting systemigrams provide a great deal of insight on the SoS and sociotechnical system it lives in; the innovation system requires additional analysis.

The related systems thinking methodology and tools help the systems engineers consider and gain insight into the complex nature of these three related systems before they begin to “engineer” their solution sets.

5.2 INNOVATION IMPACT PROCESS: A LEXICON FOR EXCHANGE OF DIGITAL ENGINEERING DATA AND MODELS

In the context of the three-system model and the systems process of transformative innovation, a series of innovation impact programs and challenges will need to be sponsored that lead to an evolutionary transformation of the enterprise. The idea that there are three systems of change across three horizons serves to continually remind us to think holistically about the transformation process. The actionable outcome of this way of thinking is a set of development/investment opportunities that channel innovation investment to the areas that have the most impact on short and long term transformation. A known impact innovation impact area is the process of digital information exchange. Viewing this in the three system context creates a conceptual model of the complete impact area. These areas are often known by the stakeholders to be important, but the systemigram process creates a more comprehensive model of the enterprise change for the stakeholders, who usually only have a small part of it in their mental models.

At the request of the sponsor, a sixth systemigram was created to focus on the digital information exchange process in the emerging digital engineering ecosystem – a known innovation impact area. This systemigram was developed to begin the process of agreement on terminology surrounding the exchange of digital information. The diagram is shown in Figure 12 with the narrative following the figure. All of the components and relationships in this conceptual model were extracted from parts of the initial five systemigrams. However the accompanying narrative is a synthesis of information exchange concepts by the research team and is not a product of the interview and other data collections processes. It provides a good example of the derived artifacts that can be generated from the original systemigram analysis and provides an artifact that can be turned into a formal model such as a Business Process Diagram in future research. This systemigram was presented and validated at a Digital Information Exchange Working Group meeting attended by a broad group of government and industry stakeholders. This is one of a number of different models that can be extracted from the original systemigrams in future work.

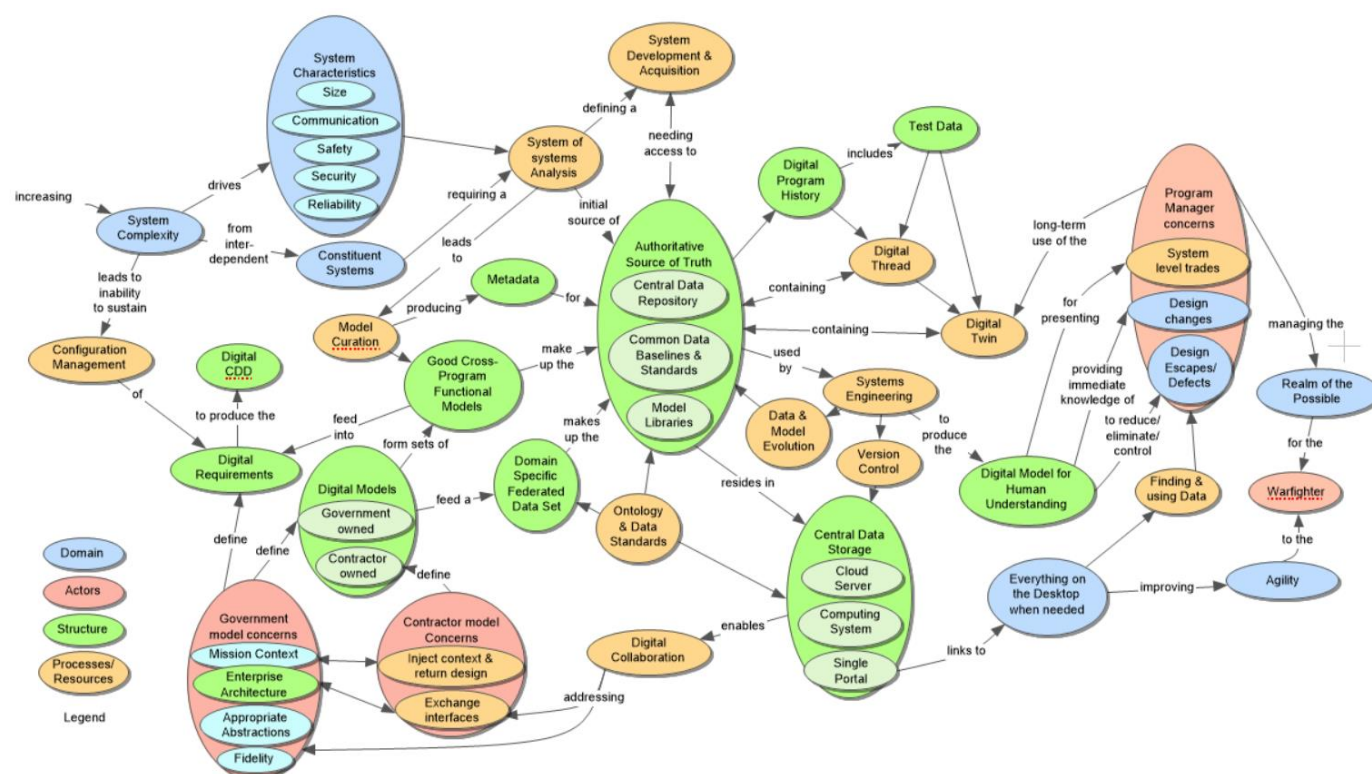


Figure 12. Systemigram diagram of the digital information exchange process.

As with previous diagrams, this story starts with increasing complexity of defense systems. The SoS characteristics and interdependencies with other constituent systems lead to the need for a robust SoS analysis to define the development and acquisition program for a new system. “SoS Analysis” is a new term that reflects the need to digitally analyze the enterprise architecture and concepts of operations for a new system as a complete SoS prior to initial acquisition decisions. Per the interview data this is either a more robust AoA or replaces the current concept of an AoA – either way it implies a new process is needed to address the system and its SoS context that reflects the complexity of new systems.

This SoS analysis will be the responsibility of the system acquirer and will serve as the initial source of data and models for the AST at a program office level. The SoS Analysis will lead to a “model curation” process that produces metadata for and populates the AST. Per other SERC research on model curation [16], one might think of this like curation of artifacts in a museum where “good cross-program functional models” are selected for inclusion in the collection of models that make up the AST. It is important to note that these are functional models, a core systems engineering representation of the system. It is also important to note that the concept of a “good model” in this context be an evolutionary process as program shift to this type of process. The curation of the functional model baseline will address both government and contractor model concerns. A significant learning process in the DE transition will be understanding and normalizing the appropriate abstractions and fidelity of the government data and model set that is provided to the contractor in the acquisition process. There are many issues to be resolved including protection of contractor intellectual property, security, etc. that will be the outcome of the curation process. This initial process will produce the initial requirements baseline for a program, driving formal requirements artifacts such as the CDD (which also needs to be redefined in a transition from paper to model driven requirements).

The government and contractor curation process will determine the government owned and contractor owned digital models that make up the “domain-specific federated data set” that feeds the AST. This also is a new terminology implying the curation is both a domain specific representation of mission and context and also as selected federation of general and domain specific models that are pulled together by the acquisition program office. The core of a successful information exchange model will be the development of both general and domain specific ontologies and data standards that different models and artifacts to interact in the digital domain. The DEXWG challenge will be the long-term development of these standards.

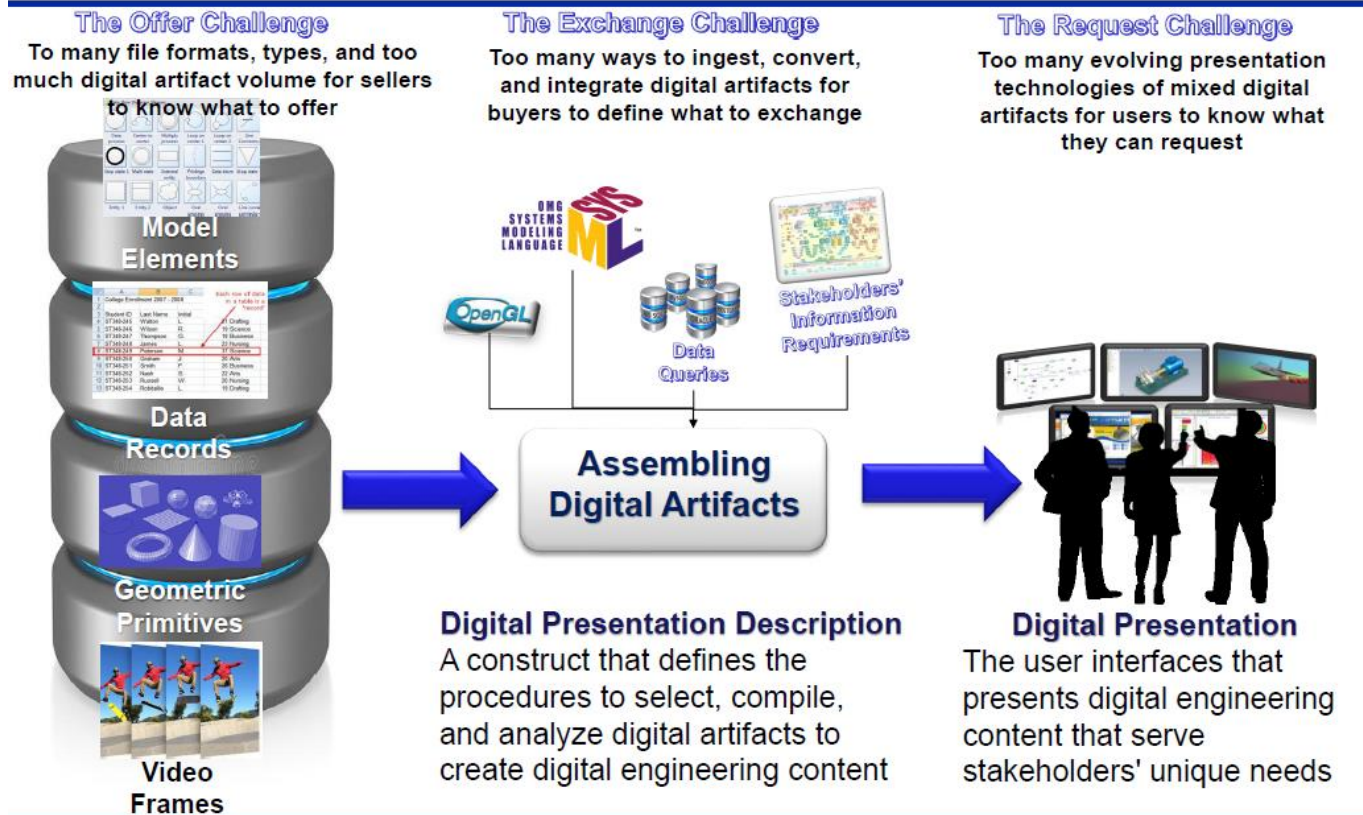
As previously discussed, the primary role of a future systems engineer will associated with data and model evolution and version control of the curated model federation in the AST. This will be a process that follows the program lifecycle as a digital program history, producing the program decision artifacts that are being called the “digital thread” and the full lifecycle artifact that gets updated with feedback in the fielded system known as the “digital twin.” A poor digital information exchange model will result in an unusable digital thread and twin, highlighting the need for a robust data and model development investment in the early phases of a program – the additional upfront investment will be repaid in cost savings at later program stages.

The outcome of the process that creates the AST is a “digital model for human understanding,” another new concept articulated in the systemigram models. Figure 13 (from the sponsor [16]) depicts generally this concept. The model representation support the program manager decision data concerns of system trades, reduced design escapes/defects, and immediate knowledge of design changes outlined in previous systemigrams. This model outcome will be enabled by an effective digital information exchange that formats and presents everything on the desktop of the decision makers when needed, automating the process of finding and using data, creating more agile decision processes and delivery of new system functions. As discussed in previous systemigrams, the full process should provide a digital baseline to rapidly explore, simulate, prototype, and deploy new functional capabilities to the warfighter that significant advance the realm of the possible in new, innovative capabilities. Figure 13 summarizes the curation process as a “A construct that defines the procedures to select, compile, and analyze digital

artifacts to create digital engineering content,” and the digital model for human understanding as “the user interfaces that present digital engineering content and serve the stakeholders’ unique needs.”



The Transformation: Conversion from Digital Artifact to Stakeholder Wisdom



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Figure 13. Process representation of a "Digital Model for Human Understanding."

The systemigram diagram in Figure 12 provides a much richer descriptive model of this transformation, allowing much more targeted innovation investment strategies as well as a story that articulates (initially) the value of this transformation. The development of robust digital information exchange models, processes, and decision data will be a make or break process for DE transformation. There is a need to develop both data exchange models and standards, and new roles and processes for model curation and exchange. The DoD strategy must enable the innovation system to step up to this challenge, and remove barriers to success.

5.3 STAKEHOLDER ANALYSIS IN THE DE STRATEGY

Based on the systemigrams, it becomes clear that the “SoS of interest” in the change process for the acquisition enterprise centers on government program office transformation from standalone and disparate acquisition documents to a new acquisition package baseline defined as data in the AST. This section highlights an initial analysis of key stakeholders in the process, and their needs or values that must be satisfied for successful change. This is based on the breadth of interviews conducted to date, and needs to be augmented in future work on a more thorough review of key actors in the innovation space.

Stakeholder Interviews

The project conducted interviews with 25 individuals across 15 visits. The visits and organizations are listed below but the individuals interviewed will not be published. An important context driver at this point is the limitation on interviewees to government organizations and government related research centers/labs. This creates a limitation in the diversity of the full narrative, but was a strategic choice agreed upon at the program start between the sponsor and research team in order to fully understand the acquisition related boundaries in the systems. Future studies should expand the interviews, facilitations, and narratives to a broader set of stakeholders. This should be done prior to a full innovation system analysis as these perspectives will be key to the innovation system definition.

In addition, the collection of interview narratives is targeted at reaching a diverse set of perspectives and does not attempt to reach all stakeholders or even a formal sample set. Any key stakeholder organizations not listed were either not interviewed due to schedule issues or because the expected interviews would not add new perspectives to the systemigram models. What constitutes “enough” interview data is a judgment call by the research team based on whether or not there are perceived gaps in the systemigram models. These models can be updated by additional interviews in the future.

Although DoD acquisition was the primary focus, the team also interviewed a number of people in the National Aeronautics and Space Administration (NASA) and Jet Propulsion Lab. This was intended to integrate lessons learned from some of their DE pathfinder programs into the narratives. These interviews were consistent with DoD perspectives and helped to fill out the models with additional experience context.

The following organizations participated in the interview process:

- Office of the Deputy Assistant Secretary of Defense for Systems Engineering (DASD/SE)
- Joint Staff Joint Requirements Analysis Division (JRAD J8)
- Secretary of the Air Force/Acquisition (SAF/AQ)
- Army Program Management Office/Aviation (PM-Aviation)
- Office of the Director of Operational Test and Evaluation (DOTE)
- Army Tank and Automotive Research and Development Center (TARDEC)
- Navy Space and Naval Warfare Systems Command (SPAWAR) San Diego
- Air Force Program Office, Ground Based Strategic Deterrent (GBSD)
- Army Program Office, Future Vertical Lift (FVL)
- The Aerospace Corporation
- John Hopkins Applied Physics Laboratory
- NASA Headquarters
- NASA Marshall Space Flight Center
- Jet Propulsion Laboratories (JPL)

In addition the narratives were augmented with published experiences from a number of other pathfinder programs via desk research.

Stakeholder shifts (interview snapshots)

Stakeholder shifts are interview snapshots from the consolidated interview narrative that represent emerging stakeholders of interest or stakeholders who have changing influence or roles in the enterprise. These are noted as narrative statements below.

“Single engineers can no longer contain a mission in their head. The mission is big enough and complex enough that if we didn’t have the single source of truth we could not all be working on one baseline.”

“[DE] has to be about SE, you have to first ask yourself if you’re doing SE.”

“A big benefit of the modeling is to stop the SE’s from doing accounting (lists) and move them to quality control of the development process. The models create more time for QC.”

“SE and software engineering disciplines will become a key part of the transformation.”

“We do not have a good way/culture to marry the emerging digital natives with grizzled veterans and their domain knowledge.”

“There is tension going on right now between old guard and new guard. Steep learning curve and these are tools that traditional SE don’t feel comfortable with... Receptivity to modeling is inversely proportional to age. A lot of the innovative stuff is early career - modeling savvy, IT savvy, digital repositories versus paper. These are wired into recent graduates. There will be an aging out process.”

“[DE] is most about being a good customer. Making sure at the PM level that we were a better informed customer with respect to what we are buying and building.”

“The team followed an onion shell analogy: super users developing the models, managers of the model, and the general SE community at the skin. The general SE community never wrote [models] and seldom used it. The model and modeling tools need to output communication media to all of the general users in a form they are comfortable with.”

“Government configuration management should see a cosmic shift. But CM and data management as it scales is a scary proposition. Need the data and information tools to manage the scale and complexity.”

“System of systems analysis requires you to have data that others have. This will be a big cultural change, government is great at creating data stovepipes. Need policy that manages the central data repository. Looking across our platforms, sometimes we have the data, sometimes the contractor does.”

“It would be nice if the organizational structure was implemented to follow the tool chains. Would organize around standards and standard libraries/data repositories.”

“In the future there are concerns about artificial intelligence (AI) and the interactions of many systems that blend human and AI. Paradigm shift.”

“Technologies that foster collaboration are key.”

“Will need to bridge the modelers to acquirer’s gap. Need tools that figure out what data we are going to buy. How do you manage data integration versus budget?”

“Communication across discipline. Especially when you try to get scientists and engineers on the same page since they don’t speak the same language. [DE is] a big tool for help bridge those gaps.”

“If you don’t have buy-in, nothing is going to happen. Need right leaders in place to drive it.”

Stakeholder Value Wheel

The stakeholder value wheel, shown in Figure 14, is a simple visualization tool that attempts to list all critical stakeholder types and their primary interest in the change in a single place.

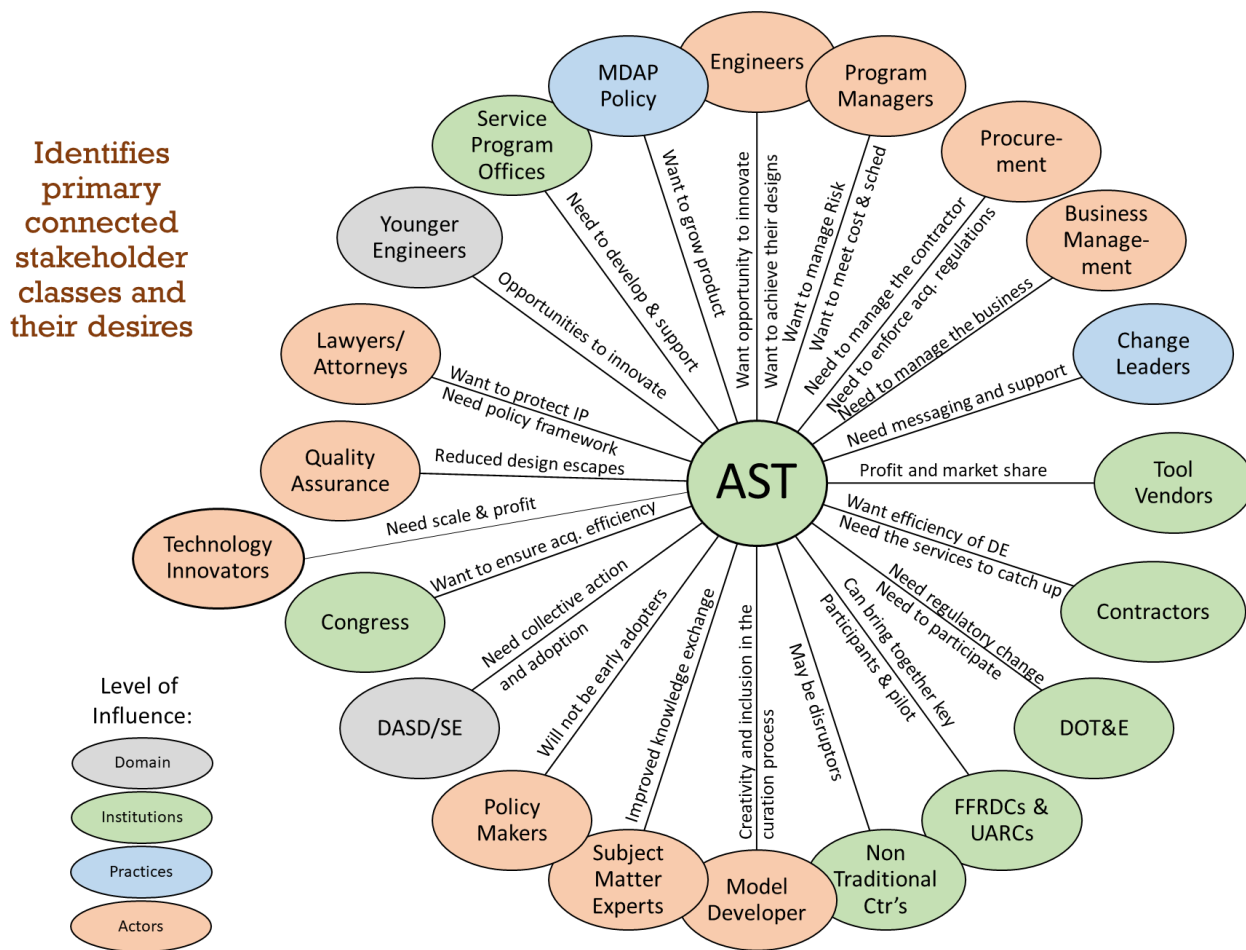


Figure 14. Stakeholder Values Wheel.

Successful transformation will be dependent on meeting or changing the primary needs or values of the key stakeholder groups. This view is presented as an artifact of the interview process at this point. Future model development can more explicitly define their metrics and roles. Key insights extracted from the narrative snapshots and this visualization are as follows:

- There will be a shift in the discipline and roles of systems engineering, primarily shifting their role from quality control of the engineering process to quality control of the engineering design.
- There will be a generation gap as experienced systems engineers, many of whom are not modelers, interact with younger engineers who come in with native digital and modeling experience.
- A role that formalizes the curation of SME knowledge into the AST, and also a role that supports curation of models, will emerge.
- Contractors and their lawyers will have to address ownership and intellectual property concerns with shared government/contractor models. This is a place where non-traditional contractors may play a disruptive role.
- There is a tremendous opportunity for technology innovators to address this transitions, the current generation of systems modeling tools are still in their infancy. Their interest is more likely to be driven by broad industry adoption rather than DoD, as digital engineering evolves a trend to become more prevalent across all industry sectors.
- Change leaders are required to transform the enterprise, primarily at the service program office and contractor product line levels. They will need to be armed with messages that articulate the value and benefits of DE and must persist in the change process.

5.4 INNOVATION SYSTEM AND ENABLERS AND BARRIERS ANALYSIS

This analysis is left to future research. The innovation system analysis is a facilitated process to refine the Three Horizons analysis and associated stakeholder relationships. The innovation system is scoped by a series of facilitated workshops that ideate of general purpose innovations (ones that build infrastructure, such a cloud environments) and cross-domain innovations (ones that transition from one market to another) will impact the SoS of interest. This defines a set of innovation impact areas that might be targeted for development in an investment portfolio or research roadmap. The second analysis focuses on specific actors in the innovation system and the enablers and barriers that would help or inhibit change. This analysis identifies actions such a standards development, investment strategies, management actions, knowledge exchange activities, etc.

The next steps section will identify specific work that might be targeted with this analysis.

5.5 LEADING AND LONG-TERM INDICATORS OF CHANGE

An analysis of metrics opportunities was developed from the systemigrams. Note that this is a qualitative analysis at this point based on conceptual modeling of the future DE-enabled enterprise. It is intended for discussion. Development of detailed metric recommendations and descriptions would require a more detailed analysis of existing metrics and service acquisition feedback on future metrics.

The systemigram analysis suggests that DE will impact 4 overall DoD acquisition performance metrics and a large number of program office level metrics. Enterprise acquisition metrics might be characterized as long term indicators of transition success, while the program office metrics contain short- and medium-term indicators. A key to successful enterprise transition is the identification of short-term metrics or “leading indicators of change” that are linked to longer term metrics, as most of the current day stakeholders in the DE strategy will likely have moved on to other roles before the long-term success or failure has been fully realized. In developing a computational and predictive model of the enterprise transformation, it will be important to identify an appropriate set of leading indicators to simulate and analyze so that meaningful predictions can be evaluated with early results. The metrics determined from the systemigrams are summarized below (in no particular order).

A. Enterprise acquisition metrics

1. Average MDAP contract length, MS B to IOC. Annual reports of defense top level metrics indicate that the average MDAP contract length from Milestone B to IOC has increased from 4 years to 7 years since 2004. The most cited reason for this is increased system complexity. Since DE initiatives are mostly in response to complexity, the gradual incorporation of DE-driven acquisition should reverse the trend in this metric. Reasons that could be tracked include improved upfront systems-of-systems analysis leading to increased operational simulation at scale, program decisions increasingly using data to drive decision-making, and reduced time to find and access data.
2. Post MS B requirements stability. 33% of program performance issues that drive Nunn-McCurdy cost breaches are attributed to instability of program requirements post-milestone B. This should improve with DE as requirements baselines move from documents to models and pre-MS B simulation of requirements increases.
3. Program reliability metrics. Weapon system reliability and availability metrics that relate to program design escapes should decrease with DE.
4. Acquisition professional certifications. DE will require new certifications for acquisition professionals. Top-level metrics of DE certification need to be developed.

B. Workforce metrics

1. DE will require more STEM capable professionals. The digital transformation will produce a need for more “data savvy” engineers, and possibly lead to a trend that reduces the average age of the DoD engineering

workforce. It will be important to track attrition metrics across the STEM labor categories to ensure that these younger professional can be retained.

2. A goal of DE is to increase the number of “A-players” in the workforce. How to define and measure this? (A research project in itself).

C. Technical data

1. When program decisions are data driven, procuring tech data should shift from a separate acquisition decision process to one that is integral to the SE process. How should this be measured?
2. “Redefining CM” was a continually stated outcome of DE, how to measure this? A change in CM plans or procedures, or a change in the CM content of SEMP might be an indicator.

D. DE initiatives

1. Metric: PMO pace of adoption of the DE strategy.
2. Metric: Number of PMO DE initiatives.
3. DE will create digital repositories of program history. Metric: Number of programs having a digital twin.
4. Metric: Number of program best practices developed in DE methods/processes/tools.
5. Metric: Number of service/program DE Communities of Practice.

E. Authoritative Source of Truth (AST)

1. Metric: Number of program office data repositories.
2. Metric: Number of programs using digital collaboration platforms.
3. Metric: Number of repositories or platforms identified as AST
4. Metric: Number of models under AST control
5. Metric: Number of data sets under AST control
6. Metric: Number of models under AST control per program
7. Metric: Number of models under AST control per phase (for example, TMRR or EMD) – this could be a leading indicator if many models start showing up in pre-milestone A phase, suggesting new programs are adopting DE
8. Metric: Number of times ASTs are accessed. Could track accesses to use models or data versus accesses to write / create / modify models or data
9. Metric: Number of reviews that are run off AST-controlled models and data
10. Metric: Number of field tests or range tests that use models or data sets drawn from an AST
11. Metric: Number of field tests or range tests that load test results into an AST
12. Metric: Number of ASTs that have individual configuration control procedures
13. Metric: Average number of approvals required to create or modify a model of data set in an AST
14. Metric: Average number of individuals who have access to a model in an AST, per model

F. Systems Engineering Processes.

1. DE will redefine developmental and operational test practices from requirements validation toward model validation goals. How will test data availability be measured in this transformation?
2. DE and associated MOSA initiatives will improve modular interaction of systems and new technology insertion. How will this be measured?
3. DE and associated MOSA initiatives will increase competitive awards and potentially small business awards for subsystems and tech insertion. How will this be measured?
4. DE will gradually eliminate manual processes, leading to more automation and increased business process efficiency. There are a number of metrics that could be defined here. The systemigrams did not produce any lower level concepts in this area. Detailed analysis of these would need to be a separate project.
5. Metric: number of high fidelity models used in program trades.
6. Metric: number of digital ICD and CDD documents.
7. Immediate knowledge of design changes between the contractor and program offices will change decision making in program management. It should decrease the overall change board metrics related to time and accuracy of change approvals.

8. Overall knowledge of the design will decrease the time and improve the accuracy of the SETR process. There are a number of SETR metrics that will be impacted by DE. The NAVAIR model-centric engineering pathfinder should provide insight into these.

G. Technical Innovations

1. Metric: number of programs using government HPC assets.
2. Metric: number of tools created specifically to examine or use models or data sets in an authoritative source of truth
3. Metric: number of tools put in service to index, manage, or configuration-manage an AST
4. Metric: number of data analytics tools used directly to support or analyze AST models and data

H. Other Acquisition process

1. The DoD capability assessment processes should over time transition to government truth data warehouses. This will change the data and decision making in the DOTMLPF process for new acquisitions. How to measure this?
2. DE should produce a shift in RDT&E costs toward pre-milestone B activities. How to measure this?
3. DE should reduce the time from service identification of threat driven capability needs (Integrated Priorities List) and Urgent Needs to the delivery of solutions.
4. DE should increase the number of representative prototypes developed in the acquisition process.

6 Recommendations and Next Steps

This report is a snapshot in the midst of a long period of enterprise change. The systemigrams created reflect one future state out of many, but one that in the combined narrative of the experts interviewed represents the most effective strategy and outcomes to follow. One might try and describe the completion of the DE transformation in simple terms like “paper artifacts are no longer used” but in truth these artifacts may never go away and the actual transition is a much more complex process with many large and small shifts. The value of the systemigram tool is it moves the description of that possible future from a slide deck or bulleted list into a rich model that captures the key relationships in the transition. Although the primary goal of this project was to produce these systemigrams, their real value will be if they continue to inform other discussions and projections, evolve the strategy, and inform wise investments and other decisions that move the change along. The artifacts in section 5 represent just a few of the additional insights that come from the original efforts.

Key Findings

1. The transformation to digital engineering envisioned by OSD’s Digital Engineering Strategy is underway. Hard evidence for this was seen throughout the interviews. DoD leadership is solidly behind the transition at the top and we found evidence of that leadership across every level of the DoD command structure. However, the number of programs embracing DE is still quite small in relation to the scale of the enterprise.
2. Numerous pathfinder efforts across NASA and the DoD are informing both the technical path and the policy and economic drivers of this change. The DoD leadership must exercise patience and apply continuous change leadership as many more pathfinders will be needed to mature the strategy. A key aspect of the workforce and cultural shift is the messaging that comes from DoD leadership on the value of DE – this must be developed and applied consistently across program offices.
3. Digital engineering is perceived by the broad community interviewed in this task in a way that naturally aligns with the five goals in OSD’s Digital Engineering Strategy:
 - a. Formalize the development, integration, and use of models to inform enterprise and program decision-making.
 - b. Provide an enduring, authoritative source of truth.
 - c. Incorporate technological innovation to improve the engineering practice.
 - d. Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders.
 - e. Transform the culture and workforce to adopt and support digital engineering across the lifecycle.
4. The infrastructure is primarily in place to support the transition, although the shift to “engineering in the cloud” will be opposed by many in the enterprise. This is a shift that is already happening broadly in the software community with DEVOPS practices and enterprise “software factories” so it will be wise to track and reuse their lessons learned.
5. There are many gaps between what is currently available in technology and processes versus what will be needed to implement digital engineering, particularly in the management of models within the Authoritative Source of Truth. This includes rigorous processes for verifying, validating and accrediting models, and distinguishing between representations of intended designs, expected performance, and current status. This also includes means for protecting the intellectual property of the model owners and the security of the models. Significant innovation is needed. Pathfinders are underway across not just defense/aerospace but also many commercial enterprises so the DoD will not need to do everything.

6. People do what we measure so the development of good metrics that reflect the leading indicators of change, primarily at the service program office level, are much needed.

Recommendations

1. **Metrics.** In order to measure progress toward an enterprise wide transformation, the appropriate measurement models should be identified and developed. A methodology for tracking these measurements should be put in place. The work on RT-182 identified a number of possible metrics for initial discussion with the service level acquisition professionals. Next steps in this work are to fully define the measurement approach and expected outcomes.
2. **Model Curation and Certitude.** A rigorous approach should be developed to verify, validate, and accredit the models that are incorporated into the Authoritative Source of Truth. Government and industry personnel who use the Authoritative Source of Truth will need to know the quality of each model and the range of data over which each model can be trusted. The process that curates, manages, and governs the models must also be addressed in the near future.
3. **AST Metadata.** A standards process should be initiated to standardize metadata for the models and data that will be incorporated into the Authoritative Source of Truth (AST). Metadata should identify the degree of accreditation and range of validity of models in the AST. Metadata should distinguish between data and models that describe requirements (the intended design), design status (the performance of the design if it were implemented today), and the expected performance of the design when it reaches initial operational capability. There are doubtless other important metadata functions beyond those listed here. The retail and service industries have made huge strides in this area with web3.0 standards and ontologies, follow their lead.
4. **Innovation.** The enterprise is evolving incrementally but there is also acknowledgement that significant process and technology breakthroughs will be needed to fully achieve the goals of the DE strategy. The DoD should use all tools they have to encourage breakthrough innovation in this area. This will be difficult as DE is a support activity and not a technology that directly affects the fight. A tolerance for creativity and safe experimentation, completions of innovation impact studies and roadmapping, and investment in methods, processes and tools must be sustained.
5. **Human Capital.** This will be a significant shift in the workplace. "Data driven acquisition" will be more natural to the "digital natives" who are entering the workforce. Still, care must be taken to engage the experienced engineers and acquisition professionals. Training programs must evolve with the strategy.

Next Steps

The successful transition in a broad sense will center on the concept of the authoritative source of truth and how the service level program offices adopt and use this construct. Further analysis is needed to capture and define the guidance at this level. One might use the mental model of "A Program Office Guide to Successful Transition" to describe this. A phase 2 facilitation that engages with select program offices adopting DE and engages a broad swath of industry (contractors, other commercial experience, tool vendors, etc.) is needed. This engagement should be focused on development of a solid metrics foundation for measuring the enterprise change process and its successes and failures. A phase 2 effort should also complete the innovation system analysis and build a strategy to address enablers and barriers to change.

Further efforts are needed to engage and define how the early and late stage ends of the acquisition community adopt and benefit from DE - these are the capabilities assessment and development, operational, and test functions.

These groups are not currently engaged in the strategy but will be critical to its success. Investment in pathfinders and strategy development must also be sponsored in these functions. The return on investment in DE will not be as much in the development process as it will be in the capability to needs arena (speed) and test (reduced design escapes). This cycle is repeated continuously in the sustainment phases of the lifecycle and large returns can be expected as the capabilities analysis adopts more model-driven practices (simulate before spending) and the test community operates continuously out of and into the authoritative source of truth.

As the transition proceeds new uses for DE and new benefits from the process will accrue. A sustained program that encourages exploring the art of the possible and understanding of the unique use cases that will evolve should be pursued. The outcome of this work should be dissemination of the lessons learned and an increase in the number and speed of the cycles of learning in this domain. This is happening today through mostly informal methods, the communication of these should be formalized, communities of practice encouraged, and forums for exchanging knowledge supported.

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7 Abbreviations and Acronyms

AoA	Analysis of Alternatives
AI	Artificial intelligence
ASD	Assistant Secretary of Defense
AST	Authoritative Source of Truth
CDD	Capability Definition Document
CM	Configuration management
CONOPS	Concept of Operations
DASD/SE	Deputy Secretary of Defense for Systems Engineering
DE	Digital engineering
DoD	Department of Defense
ESoS	Enterprise Systems of Systems
FFRDC	Federally Funded Research and Development Center
FMECA	Failure Modes, Effects, and Criticality Analysis
HPC	High Performance Computing
ICD	Initial Capabilities Document
INCOSE	International Council on Systems Engineering
IOC	Initial Operational Capability
IRB	Institutional Review Board
IT	Information technology
JPL	Jet Propulsion Laboratory
MBSE	Model-based systems engineering
MDAP	Major Development and Acquisition Program
MOSA	Modular open systems approach
NASA	National Aeronautics and Space Administration
PM	Program Manager
PMO	Program Management Office
QC	Quality control
SERC	Systems Engineering Research Center
SoS	System of Systems
SE	Systems engineering
SETR	Systems engineering technical review
SME	Subject Matter Expert
STEM	Science, technology, engineering, and mathematics
SysML	System Modeling Language
UARC	University Affiliated Research Center

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Appendix A. Context Analysis Tool Description

Exploring the wider context—referred to here as the context analysis—and problem space of interest entails data collection. Often the context is broader than, but inclusive of, the system of interest. This context influences the structure and behaviors of all of the societal features and technical systems that operate within and beyond that problem space. As such, it is imperative to understand how context affects the components that shape and drive each level of the system. This is captured at different levels in order to identify what exists in the overall system structure, what is happening in terms of processes, behaviors, and activities, and the phenomena or transformative events or trends that may shape its future state.

By using a context analysis table to organize data, a team is better positioned to appreciate the phenomena that drive activities within the system layers—in social systems the micro, meso, and macro, or in enterprise systems people, process, institutions, and domain. These levels of the system correspond to features of context analysis, these include (1) Enabling Environment (2) Actors and Input (3) Interactions, and (4) Output and Outcomes. This helps users organize and visualize system boundaries, appreciate a system’s bearing upon the problem space, and understand drivers, and identify those that are possible in the future system. Furthermore, placing data into a Context Analysis Table can be performed on an ongoing basis through an iterative process. As understanding of the problem space evolves, the relationship to and understand of context may evolve as well, such that the table can revisited for reference or modification as deeper insight emerges.

Process steps:

1. Identify the Enabling Environment and Key Actors/Inputs for each level

Many types of entities can exist in a system, and they are not strictly structural components that can be observed. Entity types include people, groups, organizations, and societies. They also include artifacts like resources, tools, products, infrastructure, and the environment. Additionally, more intangible items like services, mission or strategy, regulations, and policy may be included. For this step, brainstorm what might exist at each level. Consult content experts as necessary to fill out the list. Focus on types of entities more than specific examples unless the specific entity has a dominant position in the system of interest.

2. Identify the Interactions at each level

This step looks at processes, activities, and behaviors. Focus on statements that describe transformations that occur between entities in the system. For example, “cooperatives help farmers organize” describes two entities (cooperatives, farmers) and one transformation (organize). Brainstorming and consultation with experts helps in this step.

3. Identify the Outputs/Outcomes observable each level

Phenomena are defined as observable facts or events that are unusual or hard to describe. The best way to identify and capture descriptions of phenomena is to read literature pertinent to the system, exploring it from different perspectives. Reading about current real world events is helpful, as they tend to emphasize interesting phenomena in the system as it exists today or as it may be trending in the future. List statements that describe phenomena in the system. The following template illustrates the organizing principle of the Context Analysis Table.

	Enabling Environment	Actors (and what they bring with them)	Interactions/ Activities	Outcomes
Domain	Governmental regulations, law, policy, infrastructure, environment, geography, economic conditions, security, National innovation strategy	Governments, Nation-states, regions, Infrastructure mgmt., International cooperatives, Non-government groups	Economic trends, Demographic trends, Shifts in governance, Network attributes, Ideology, Market shifts	Buy-in and acceptance, Employment rates, Goal attainment, Success of policy, New infrastructure, Growth, Change
Institutions	Ownership, Production environment, Distribution network, Import/export controls, Standards	Government organizations, Commercial organizations, Universities, Research institutions, Lobby groups, Segments, Unions, Incubators, Societies	Market access and control, Resource access, Access to credit, Technology transfer, Organizational relationships,	Capacities, Disruptions and continuity, Resilience and efficiency, Product/process, Cooperation, Strategy
Processes	Legal structures, Demand, Pricing, Best practices, Standards, Contracts/agreements	Work practices, Training, Management structures, Innovation practices, Strategies, Employment structures	Information flows, Resource flows, Knowledge flows, Financial flows, Work activities, Customer interaction	Buying, Selling, Technology uptake, Market leadership, Collaboration, Effectiveness of programs
People	Culture, Networks, Community structure, Religion, Access to information, Proximity to resources, Property rights	People, Entrepreneurs, Health, Technologies, Capital	Production, Consumption, Income, Membership, Teaming, Learning	Standard of living, Wellbeing, Wealth, Employment, Health, Education, Trust

Actors (and what they bring with them)					Interactions/ Activities	Outcomes
Enabling Environment						
Domain						
Institutions						
Processes						
People						

Appendix B. Interview Protocol

RT-182 Interview Protocol

INTRO

- SHORT INTRODUCTION TO THE RT-182 GOALS
- WHO ARE WE AND WHY ARE WE DOING THIS
- HOW MANY MINUTES WILL THIS INTERVIEW BE
- THE GENERAL FLOW OF QUESTION AND WHY WE'RE ASKING THEM

OPENING DISCUSSION:

What is "Digital Engineering" in a sound bite?

*"Digital Model-based Engineering (DMbE) is the use of digital artifacts, digital environments, and digital tools in the performance of engineering functions. DMbE is intended to enable practitioners to engineer capabilities using digital practices and artifacts in a collaborative environment, creating a digitally integrated approach with a federated single source of truth. [...] DMbE is intended to allow an organization to progress from documentation-based engineering methods to digital methods that may provide greater flexibility, agility, and efficiency."*¹

Let's review the stated goals of the defense department's "Digital Engineering" initiative (to move the focus of our discussion from "what it is" to "what it should do"):

1. Inform decision making through increased transparency, and greater insight
2. Enhance communication
3. Increase understanding for greater flexibility/adaptability in design
4. Increase confidence that the capability will perform as expected
5. Increase efficiency

OPENING GENERAL QUESTIONS:

1. Tell us a bit about your role.
2. A rather broad question, but tell us about your knowledge of systems engineering, model-based systems engineering (MBSE), and the defense department's "Digital Engineering" initiative, and how these are being used today. From your perspective, what is the relationship between MBSE and Digital Engineering?
3. Another broad question, will "Digital Engineering" change the work your group does? In what ways?

CHANGING HORIZONS:

1. You mentioned some issues. What activities or practices cannot be sustained in the current defense acquisition process as we know it today?
2. Thinking of the process and change to a digital model-based engineering baseline across the next several years, what would cause you to have the worst nightmares?
3. If you were in complete control of the process, what would systems engineering and related defense acquisition activities look like 10-15 years from now?
4. If you had someone from the future describe that to you, what would you want to know?

¹ Model-Based Systems Engineering (MBSE) Infusion Task Team, Interagency Working Group on Engineering Complex Systems (IAWG), "Digital Model-based Engineering: Expectations, Prerequisites, and Challenges of Infusion" (March 2017)

5. Looking back on how the internet has changed many of your activities and experiences, how might it continue to change defense acquisition in the next several years?
6. If some of these changes come about, which stakeholders might be positively affected and which negatively?
7. Who are the most likely agents of or promoters of these changes?

TECHNOLOGY:

1. How have new technologies changed systems engineering support to acquisitions over the last several years?
2. Are there any newly emerging technologies that may be useful in this domain?
 - a. Useful in which way?
3. How receptive is the systems engineering and acquisition community to the adoption of new technologies and processes? Can you describe some examples?
 - a. Follow ups: Who used these? Did they find them useful?
 - b. If digital data was exchanged, who received access to the data?
 - c. Can you describe how technologies and processes were implemented?
4. Who is pursuing new technology solutions related to systems engineering and acquisition?
 - a. Are they developing the technology themselves, or buying it?
 - b. Who might have made the decision regarding the adoption of new technologies?
5. If a new technology solution is useful, how does information about this solution spread across the industry?
6. Is the “technology innovation community” addressing the needs of the systems engineering and acquisition community?
 - a. What should this community be focused on?
 - b. How would you convey your needs to the technology innovation community?
7. Do you have any examples where you think technology has improved the efficiency and effectiveness of the community?
 - a. Follow on: probe about some specific opportunities for impacting efficiency/effectiveness:
 - i. Modeling for risk management
 - ii. Modeling for reuse
 - iii. Modeling for agility

WORKFORCE:

1. Do we have the technical workforce to transition towards a model-based data review instead of a paper-based review?

DOMAIN LEVEL:

1. What is the role of the defense acquisition process and how has this role changed in recent years?
2. How have OSD/Service initiatives in MBSE changed the defense acquisitions process?
3. What has been the level of integration and coordination between different acquisition offices?
4. How does one determine or judge the value or impact of significant acquisition changes?

COLLABORATION:

1. How does the community use collaborative relationships and networks to meet its needs?
2. Have these relationships changed recently? How?

DATA SHARING AND INTELLECTUAL PROPERTY:

1. What are the “sacred cows” with respect to data sharing and how do they drive behavior?
2. Can you think of examples of how data sharing could be facilitated without raising IP concerns?

KNOWLEDGE TRANSFER:

1. Who are the central entities or “hubs” of knowledge as related to systems engineering, model-based systems engineering, and defense acquisition?
2. Do you think this type of knowledge is open or transparent to the community? Examples?
 - a. If so, how is this knowledge disseminated?
3. What knowledge do you wish you had but cannot get?

INNOVATION STAKEHOLDERS, ENABLERS, AND BARRIERS:

1. Who within the community has influence on innovation specific to digital engineering, and how strong is their influence?
2. How strong are the incentives (re: financially, goals/values, future activities, influence) of these stakeholders to undertake innovation in this domain?
3. Can you think of examples of how innovation is being supported?
4. Can you think of examples of how innovation is being thwarted?

CLOSING GENERAL QUESTIONS:

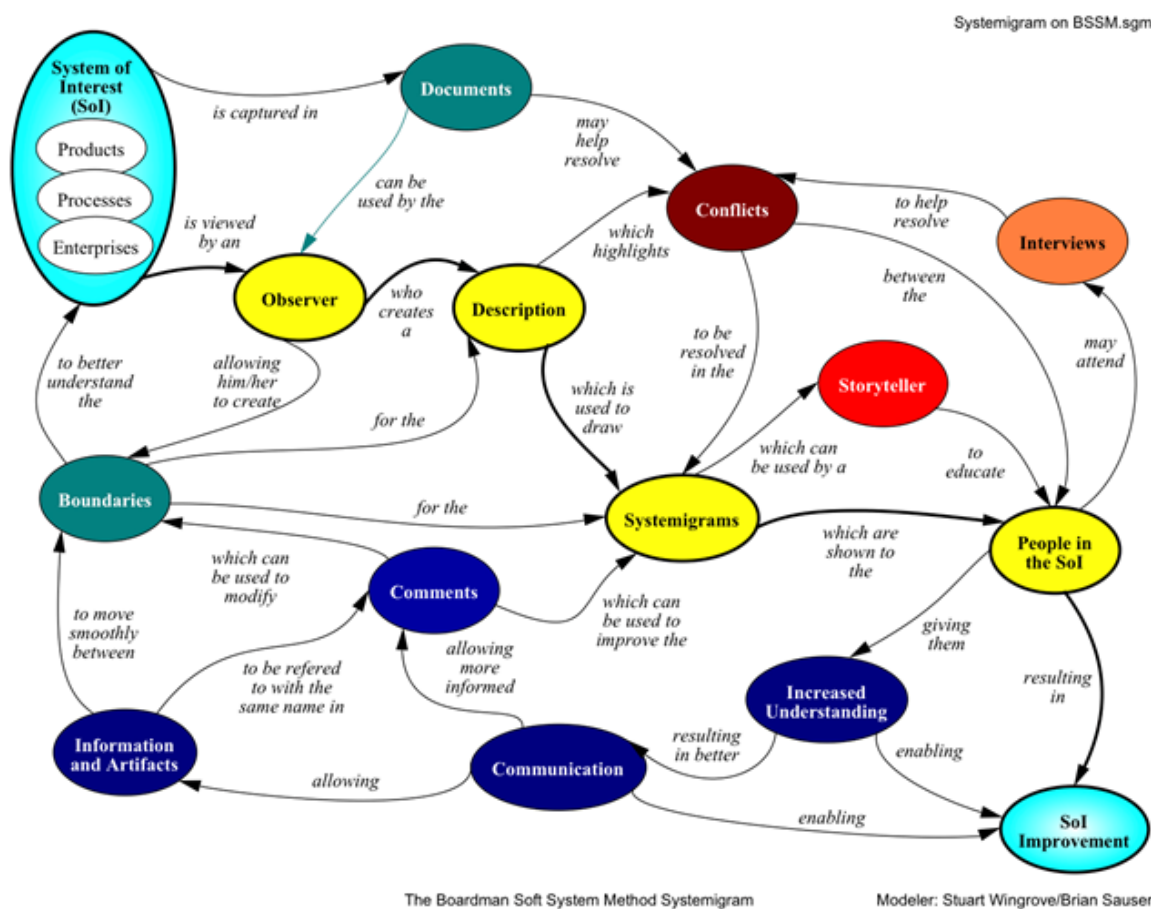
1. “Learning about your role has been fascinating. We’d like to close the interview by zooming out a bit further. There are many players who interact with the defense acquisition process. Are there other people or institutions in the system that you have engaged with who didn’t come up in our interview? Thinking of them in the context of this discussion, would you add or change anything?”
2. Please, if you can, identify any other individuals that you think we should talk to.

Appendix C. Systemigram Development Process

Systemigrams can be used to model a system. They offer a framework for elaboration with both narrative and visual details of a system's construction, root behaviors, and overall operation, while capturing internal and exogenous variables that affect how a system behaves. This tool offers three benefits; it enables (1) observation of system interactions, (2) visualization of systems features—actors, interactions and relationships, processes, etc.—as they change over time, and (3) a framework for agreement on boundaries and contexts in which to address the system. The systemigram maps the knowledge created by engagement of researchers, stakeholders, and sponsors in the study of a problem space. Its development promotes an iterative and inclusive process of system understanding. This approach spurs deeper levels of insight and appreciation of the systems through which problems, solutions, and contexts bear on innovation potential.

Constructing a systemigram involves both writing a short narrative of the crucial elements in the system that are most likely to change and how they might change, while in parallel developing 1-page diagrams that model entities and relationships captured in the narrative. Production of systemigrams is not a one-time feature of problem assessment. Rather, this tool can be used multiple times to elaborate features of systems under various scenarios. The more a team learns, the more their systemigrams can and should change to reflect deeper insights.

Example of a Systemigram Diagram:



In this example, experts Wingrove and Sauser construct a systemigram that captures the narrative on the production of systemigrams (narrative not shown). Not only does the example illustrate the organization of a systemigram visual, but also offers helpful content and insight regarding the actual practice of using this tool.

Process Steps:

1. Frame the Purpose and Identify Research Objectives

The first step entails establishing a clear rationale for the use of the tool in conjunction with the sponsors of the research. This involves defining a problem space and a context of interest. If multiple contexts are of interest, multiple systemigrams will be produced, after which teams can generalize across contexts. Once these considerations are made, clarifying the objectives and rationale of the research to ensure novelty of approach and potential limitations comes next. The Heilmeier Questions are a set of straight-forward questions that, if answered, help the user identify key areas of research necessary to support a sponsor's objectives.

2. Collect Data on Today's System and Tomorrow's System

Exploring the wider context—referred to here as the context analysis—and problem space of interest entails data collection. Any existing background information, resources, or research on hand in this area should be compiled, organized, and digested. As with most system mapping methods, data collection starts with the structure and behaviors currently observed in the system, as well as structures and behaviors considered possible in the future system.

A useful data collection template that supports production of a systemigram is called a Context Analysis (a template of which is included). Use the columns within the Context Analysis Table as the starting point for organizing research, guided by problem space features: (1) Enabling Environment (2) Actors/Inputs (3) Interactions and (4) Outputs/Outcomes. Placing data into the Context Analysis Table can be performed on an ongoing basis. Additional synthesis of knowledge occurs in the following steps.

3. Identify Central Questions of Interest (CQIs)

Central Questions of Interest (CQI) investigate how the system works and will change over time. These broad, high-level questions align with program goals and objectives. Selecting the CQIs is a collaborative decision and one best made in a group setting, after the team reviews and explores the Context Analysis templates produced in Step 2. Optimally, the team should arrive at two to three CQI's in a group discussion with the sponsors of the project and other experts as needed. CQI's unearth not only the major issues of today, but also the likely issues in the future and why those questions are likely to matter.

4. Define Key Phenomena

Phenomena are defined as observable facts, trends, or events that are unusual or hard to describe, which may be negative or positive. Events may consist of a decision or occurrence such as a bilateral agreement of natural disaster, while trends may consist of flows or shifts, such as demographic changes. These may impact the current or ongoing state, or may be indicators of future growth or future states. Key Phenomena reflect physical, behavioral, or organizational aspects of a system. They are captured and described in terms inputs, processes, and outputs for entities in the system. Identifying these diverse variables involves an iterative and inclusive process throughout the systemigram construction, which are often being revisited, reconsidered, or expanded upon. Those associated with the CQI's are derived during a workshop setting, expert meetings, or through research into the problem space. Use the fourth column of the Context Analysis Table as a guide to the type of phenomena to address.

5. Select or Develop Scenarios

Scenarios are used to explore current or possible future phenomena at each level of the system. Scenarios can also investigate or elaborate interactions between the system layers. Scenarios can be selected or developed in a

number of ways. They may be developed at a separate scenario planning exercise. Alternatively, scenarios may be collected from or inspired by relevant literature. The team should agree upon scenarios that offer a few select representative cases to narrow the focus toward leading indicators and issues, key drivers, and expected outcomes likely to arise within the scenario described. The selected scenarios should focus the team on what is emerging or what might emerge in the system as opposed to any specific predicted or desired outcomes.

6. Construct Narratives

Once a scenario or set of scenarios is selected, qualitative descriptions of the system are finalized in a set of narratives, which seek to assess the broader system in which a problem space exists. The narratives constitute an integrated formulation of stakeholder worldviews, transformation, and system development, with the intent to illustrate present-day context and describe how it may change in the future. As such, they should not be extensively or predominantly problem-focused or solution-focused, avoiding far-off or overly optimistic forecasting of alternatives in attempt to search for innovation potential.

Each narrative orients around a single context related to a scenario developed in Step 5. Overall, a narrative should capture a system's unique actors, phenomena, and organization, and offer sparing but insightful analysis of key relationships and interactions to depict the system's development and behavior. These can include regional dependencies, factors driving a change in the political or socio-economic geography of the central beneficiaries, supply and demand, or physical supply chains, to reflect what is driving the system and toward what it is moving. Key organizational components in the narrative include:

- Problem of interest and desired goal: Briefly identify and define the problem space existing in the system and why it is relevant;
- Set the scene: Describe the broader system's major actors, political or social environment, entities, components, and/or organizations that are actively present in shaping it;
- Assess behaviors, relationships, and interactions: Analyze how these system components interact that shape the system's development;
- System development and end-goal: Consider how these factors contribute to the system moving toward the future scenario selected for the narrative; include the drivers affecting or shaping the system behavior and development.

Narrative length varies, but should aim to be around one page long or less than 2,000 words. Depending upon the number of scenarios elaborated, unique narratives exploring the transformation from the current system toward any of these scenarios of interest can be formulated.

7. Begin Diagram Construction

When reading a systemigram, the nodes are taken from the textual narratives written for each scenario, and represented in the diagram. Critically, the diagram must be faithful to the narrative and original prose. The diagrams should illustrate the entire narrative. Teams should maintain focus on the components and relationships most critical to the system, wherein it helps to distinguish them in the narrative by underlining, highlighting, or other coding, to allow easy identification and extraction into the design.

Identify key actors, organizations, artifacts, conditions, and processes that shape the system. Begin creating preliminary nodes (resembling "bubbles" in the diagram). Nodes may contain other nodes, wherein they can be grouped, this can indicate breakout of a document or an organizational/ product/ process structure. The use of node color can further distinguish roles and structure in the system, Node color can vary according to component

type, such as resources (green), actors (blue), institutions (orange), or phenomena (red). Color may be used to draw attention to subfamilies of concepts and transformations.

8. Identify Entry Point, Central Theme, and End Goal

As your nodes begin to populate, start to consider their position in the system in relation to the diagram. The upper left hand corner is the beginning of the system. The bottom right hand corner is where the systemigram ends, and reflects the perceived end goal of the system, although it is not in itself the end purpose altogether. The mainstay for each systemigram is shown from the top left hand bubble, representation the system entry or starting point (such as the problem statement), which leads and connects into the various phenomena, processes, or actors, reading diagonally downward and towards the end in the bottom right, which mostly relates to the systems end goal or objective. This will aid in organizing the nodes in terms of the diagram's geography and capturing the flows between the components. Geography of systemigram may be exploited to elucidate the "why," "what," "how" in order to validate the transformational aspect of the systemic model.

9. Capture Node Interaction and Relationship With Arrows and Verbs or Phrases

Arrows or links are used to reflect the flow, interaction, or relationship between system components. Depending on the interaction, they can direct the flow to a single node, group of nodes, or sub-node. In some cases, these arrows may be bidirectional. However, crossover of the links or arrows in the diagram should be avoided. The arrows connecting the nodes are accompanied with a verb or phrase (usually taken verbatim from the narrative) describing the relationship. These verb phrases or occasional prepositional phrases are used to indicate transformation, belonging, and being. These node and link phrases capture the storyline of the narrative and are useful when following the system's threads.

10. Complete Diagram Construction and Consider Other Design Components

Consider using thickness of arrows, size, and/or color of circles, to illustrate the degree the component or relationship is prominent in the narrative. These design choices are each up to the team. A legend classifying the node coloring may be introduced in the bottom corner of the diagram as reference to readers. The team can develop its own simple key to allow viewers to understand the significance of color/size/flow, etc. within the visuals produced. They may also consider constructing diagrams specific to just one layer within their Context Analysis Tool, then comparing across them to observe distinctions about what occurs at each layer within a particular context or point in time.

11. Discuss the Systemigram and Identify Emergent Properties through Iterative Process

When the preliminary systemigrams are completed, read the diagram and narrative in parallel to inspect the degree to which both accurately tell the same story. Building pairs of visuals—one for the present and one for the future—allows the team to compare diagrams and observe how the system changes. Repeat this process for each narrative (one narrative is produced for one context). Make necessary modifications as needed.

One of the systemigram's greatest strengths is the manner in which it fuels debate, discussion, and learning within the team and among critical stakeholders regarding the changing nature of the systems in which problem spaces and opportunity for innovation exist. Thus, a workshop setting is great for the process of building, vetting, and augmenting systemigrams. An iterative and inclusive process wherein a team and/or experts builds up more comprehensive understanding of the problem space and allows participants to validate the manner in which that development is illustrated in the systemigram. At this time, input is solicited for each node and link "phrase" to add, delete, or change relationships, as stakeholders discuss and agreed upon the properties to co-create the final

systemigrams as a group. Once vetted, the visuals that portray the current and future systems should be examined and contrasted to extrapolate and exploit the insights surfaced with this tool.

In general, systemigrams should align with the following rules (adapted from Blair, Boardman, and Sauser, 2007).

Narratives

1. Address broad strategic intent and purpose of system entities (structures, relationships, etc.), not low level tactics.
2. Be well-crafted, engaging the mind of reader and author to explore the system.
3. Use facilitation and dialogue with stakeholders (owner/originator of strategic intent) to create and review the structured text and reflect their intent.
4. Be brief: though length is variable, generally less than 2000 words is optimal; the scope of the prose must fit the scope of the resulting systemigram.

Diagrams

1. The diagram should be sized for a single page that can be drawn by hand or created on such platforms as www.inspiration.com, which was designed for concept mapping.
2. Required entities are nodes, links, inputs, outputs, etc. Nodes can have inputs and outputs that are not linked to another node. The flow of links across multiple nodes should clearly reflect the beginning and end of the storyline.
3. Nodes represent key concepts, or nouns specifying people, organizations, groups, artifacts, and conditions.
4. Links represent relationships and the flow between nodes, verb phrases (occasional prepositional phrases) indicating transformation, belonging, and being.
5. Nodes may contain other nodes. Nodes within another node represent belonging to a higher level of structure or aggregation.
6. For clarity, the systemigram should contain no crossover of links (i.e., no lines should overlap or intersect).
7. Based on experience, to maintain reasonable size for presentation purposes, the ratio of nodes to links should be approximately 1.5 nodes for every link.
8. The simplest flow of a systemigram is from top left to bottom right.
9. The visual geography of a systemigram may be exploited to augment the narrative, with more observable relationships toward the middle of the visual and less important or future relationships along the periphery.
10. Color may be used to draw attention to subfamilies of concepts and transformations.

References:

http://boardmansauser.com/Worlds_of_Systems/Thoughts.html

John Boardman and Brian Sauser, *Systems Thinking: Coping with 21st Century Problems*, CRC Press 2008.

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